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Real-Time Tracking of Mass Hauls in Infrastructure Construction Project

Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology.

Espoo, 31th March 2019
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Diplomityön tiivistelmä

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Tiivistelmä

Rakennusalan tuottavuus on kehittynyt huonosti jo pitkän ajan. Heikko tuottavuuden kehittyminen voi olla seurausta alan erikoispiirteistä, kuten esimerkiksi projektien ainutlaatuisuudesta, heikosta teknologisten työkalujen käytöstä ja heikosta johtamisesta. Samaan aikaan monet muut alat ovat onnistuneet kehittämään tuottavuutta hyödyntämällä uusia teknologioiota. Monet tutkimukset ovat osoittaneet, että rakennustyömailla ei kerätä tarpeeksi luotettavaa tietoa. Tietoa kerätään manuaalisesti, mikä ei ole vain työlästä, mutta myös altis virheille. On olemassa tarve reaaliaikaiselle tiedonkeräykselle paremman johtamisen mahdollistamiseksi.

Tutkimukset reaaliaikaisten paikannusteknologioiden käytöstä ovat näyttäneet lupaavia tuloksia tiedonkeruun automatisoimiseksi ja ajantasaisen johtamisen mahdollistamiseksi. Infrarakennuskohteiden maarakennustöissä on suuri kehityspotentiaali tuottavuuden parantamiseen reaaliaikaisten paikannusteknologioiden avulla. Tässä työssä tutkitaan reaaliaikaista massojen seurantaa yhdellä infrarakennustyömaalla. Työn tavoitteena on kehittää uusi malli maarakennustöiden optimoimiseen käyttäen hyväksi reaaliaikaista massojen seurantaa. Aikaisemmat maarakennustöiden optimointimallit eivät ole pystyneet mukautumaan jatkuvasti muuttuviin olosuhteisiin tehokkaasti ja ovat alttiita hukalle. Lisäksi tavoitteena on tunnistaa kehityskohtia maankaivu ja -ajo prosessista ja arvioida mitä muita hyötyjä reaaliaikaisen paikannusteknologian käytöllä voisi olla.

Työ toteutetaan suunnittelutieteellisenä tutkimuksena. Tutkimus sisältää kirjallisuustutkimuksen, empiirisen tutkimuksen, ratkaisuehdotukset, tulokset ja yhteenvedon. Kirjallisuustutkimuksessa käsitellään olemassa olevien maarakennuksen, maanajon ja reaaliaikaisten paikannusteknologioiden nykytilaa ja tutkimuksia. Empiirinen osuus sisältää reaaliaikaisen massojen paikannuksen testityömaalla.

Tulokset osoittavat, että reaaliaikaiset paikannusteknologiat helpottavat tunnistamaan kehityskohtia prosessista ja mahdollistavat korjaavien toimenpiteiden tekemisen aikaisemmin. Maarakennustöiden kustannuksia ja kestoa on mahdollista vähentää merkittävästi käyttäen luotua optimointimallia. Potentiaalisen hyödyn määrä riippuu projektin ominaisuuksista ja maatöiden suuruudesta.

Avainsanat reaaliaikainen paikannus, massojen seuranta, maarakennus

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Abstract of master's thesis

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Abstract

Construction industry suffers from weak development of productivity. Poor productivity development may result from different attributing factors such as project uniqueness, weak utilization of technology and poor management. In the same time, many other industries have increased productivity with better utilization of technological solutions. Several studies have observed that not enough effort is done at construction sites to gather reliable data. In addition, data collection is currently done manually which is both labor consuming and prone to human errors. There is a need for automated data collection to enable better management.

Real-time tracking technologies have shown promising results answering to this need for automatized data-collection and enabling real-time management. This thesis examines using real-time tracking system of mass hauls in infrastructure construction project. Thesis aims to optimize excavation and mass hauling process utilizing real-time tracking system. None of the available earthwork optimization models are very good at adapting to changing conditions and thus are prone to poor utilization rate of machines. Aim is also to identify areas with potential for improvement in excavation and mass hauling process and make control actions to reduce waste and improve performance. In addition, thesis estimates other possible benefits of the real-time tracking system.

The research method of this research is Design science. The thesis consists of a literature review, empirical research, solution proposal, results, conclusions and proposals for further studies. The literature review displays the existing situation of the excavation and mass hauling process, existing earthwork optimization methods and real-time tracking solutions and experiments. The empirical research consists of a field experiment to test real-time tracking of mass hauls in infrastructure construction project.

Results show that real-time tracking system of mass hauls helps both to identify unproductive practices and to execute control actions sooner. Results also suggest that using the developed earthwork optimization method it is possible to reduce construction project costs and duration. Potential benefit depends on project characteristic and volume of earthworks. Larger earthwork projects incur higher potential benefits.

Keywords real-time tracking, mass hauls, earthworks

Preface

Inspiration for this thesis gave my own experiences with manual data collection methods, earthworks and management in infrastructure construction sites. I founded it challenging trying to control or analyze earthworks with traditional methods. Constantly changing conditions and thick bunch of travel documents made it a nontrivial task. Luckily E.M. Pekkinen Oy had like-minded people working wanting to develop the process and suitable infrastructure construction site was found.

First, I would like to thank Topcon Positioning Systems for granting me this opportunity to test their Haul Truck application. Thank you also for loaning me tablets and providing me with all your expertise and knowledge. Especially I want to thank Jenna Ikonen and Henry Stenberg who helped me during this time. This thesis would not have been possible without you. I want also to thank my fellows at work for constantly asking when I'm finished with the Thesis.

The writing process was both challenging and joyful experience. The challenging part was to find enough time to write between work projects and last university studies, but the joyful part was when I was able to deepen into the subject. It has been great learning experience that I think will continue even after this Thesis.

I want also to thank my supervisor Professor Olli Seppänen and thesis advisor Risto Sell for your contributions. Your comments have been the most valuable. Above all I want to thank Inka for all the love and support during this time.

Espoo 31.3.2019

Sami Merelä

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1 Introduction

1.1 Background of the Study

Construction industry suffers from weak development of productivity. Figure 1 shows Multi-factor productivity in comparison to other industries in Finland. The Figure 1 is based on the productivity surveys conducted by the Statistics of Finland. When comparing productivity in construction, manufacturing and transportation and storage industry, construction industry has been in decline while other industries have been growing.

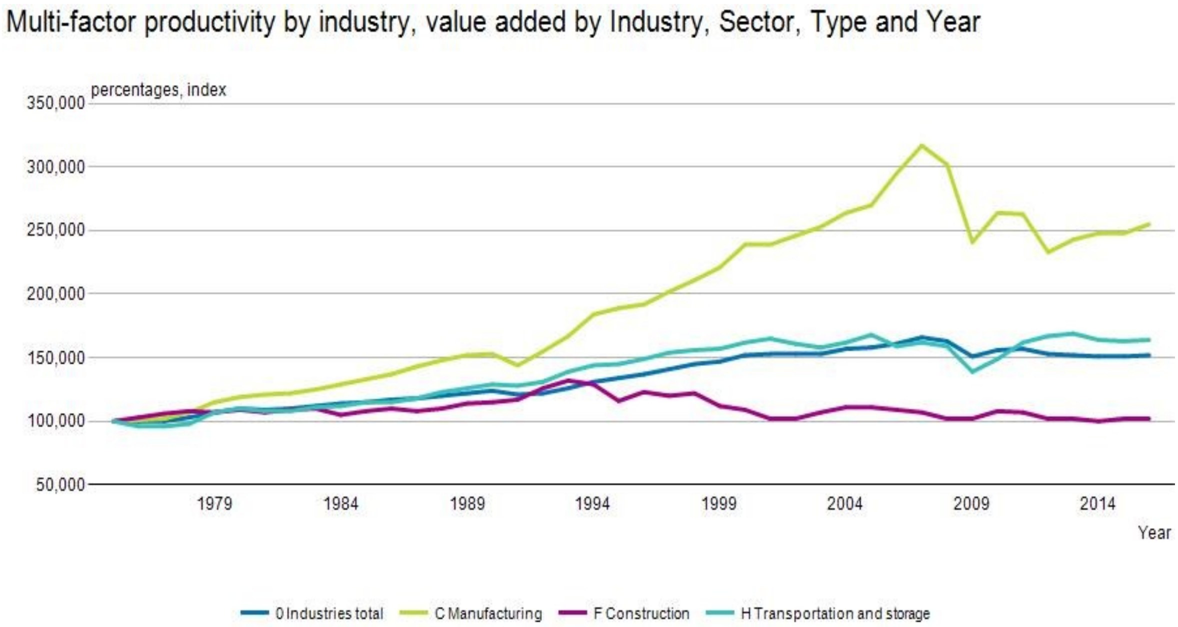


Figure 1. Multi-factor productivity in Finland 1976-2017 (Statistic Finland, 2018).

Lagging construction productivity is not only regional problem, instead it is a global phenomenon. McKinsey has estimated that “globally labor-productivity growth in construction has averaged only 1 percent a year over the past two decades, compared with growth of 2,8 percent for the total world economy and 3,6 percent in the case of manufacturing” (Woetzel et al. 2017, p.4). Figure 2 shows global labor-productivity growth trends based on sample of 41 countries.

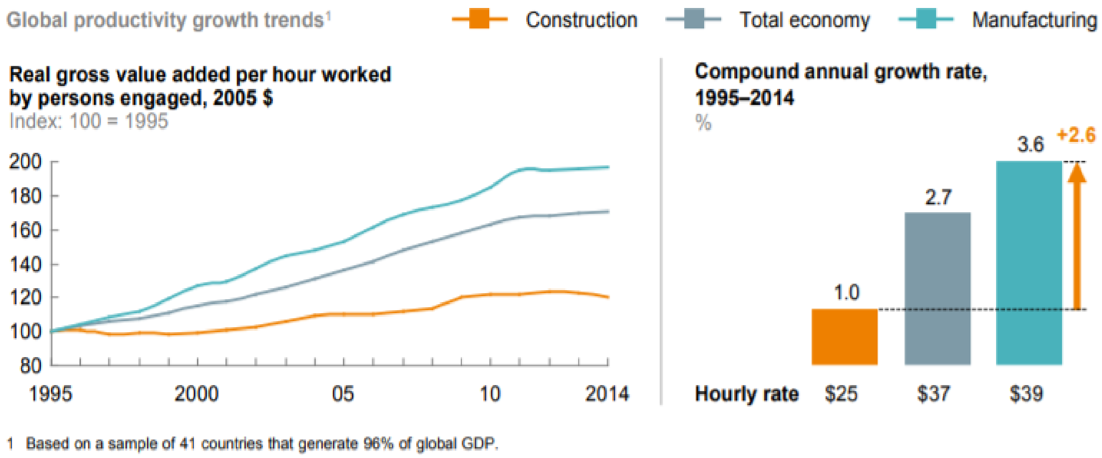


Figure 2. Global productivity growth trends of construction, manufacturing and total economy (Woetzel et al. 2017, p.8).

If construction labor-productivity were to achieve the labor-productivity of the total economy, the industry's added value could increase globally by $1,6 trillion a year (Woetzel et al., 2017). Hence, performance improvement of the construction industry can have significant impact on national economies (Navon, 2005).

Construction industry's poor productivity may result from different attributing factors such as project uniqueness, weak utilization of technology and poor management (Allmon et al. 2000). In contrast to manufacturing industry, construction projects are rarely built in the same manner as previous projects (Ying and Tookey, 2017). Changing environmental factors such as varying location, landscape and weather conditions creates unique situation for every project. In addition, project personnel are different in each project and number of workers adjust constantly during different phases of construction. Managing the project with such variabilities can be challenging. This constantly changing environment makes it difficult to separate contributing factors to productivity. (Kirchbach et al. 2014).

However, transportation industry has managed to increase productivity albeit it is subject to similar unique aspects as construction industry (e.g. varying location, weather conditions). When comparing these industries from technological point of view, it can be established that the use of passive data collection technologies is greater in transportation industry. While data collection is done manually at construction sites (Navon et al. 2004), transportation industry has adopted ITS (intelligent transportation systems), AVL (automated vehicle location) and AFC (automated fate collection) technologies which have shifted the industry from a data-poor environment into a data-rich environment (Ma and Wang. 2014). This may be one contributing factor why transportation industry has surpassed construction in terms of productivity. In the past, transportation industry had a problem that traditional data collection methods were costly and inaccurate (Simon and Furth 1985). Construction industry is currently suffering from similar problems.

Several studies have observed that not enough effort is done at construction sites to gather reliable data and the collected data is not distributed well (e.g. Laufer and Tucker 1987, Navon et al. 2004). This may be because manual data collection is too time consuming or proper technologies have not yet been introduced. Navon and Shpatnitsky (2005) determined that insufficient data collection methods leads to the problem being longer undetected. The longer incorrect behavior can remain undetected, the larger is the potential damage it can cause. There is a need for automated data collection to enable better management that can take corrective measures in real-time (Sacks et al. 2003).

Real-time tracking technologies have been shown to deliver promising results answering to the need for automating data-collection and real-time management. This thesis examines using real-time tracking system in infrastructure construction project. In addition, thesis proposes a new model for earthwork optimization using real-time tracking system and estimates what other benefits system could provide.

1.2 Research Objectives

The main objective of this study is to investigate excavation and mass hauling process of an infrastructure construction project with a real-time tracking system. The following specific objectives and research questions were formulated and addressed in the study:

Objective 1
To design optimization model for excavation and mass hauling process.

1. What is the optimization model for excavation and mass hauling process using real-time tracking system?
2. What are the benefits of using this optimization method?

Objective 2
To identify areas with potential for improvement in excavation and mass hauling process and make control actions to improve performance.

3. What potential for improvement were identified?
4. What control actions were done?
5. What were the results of control actions?

Objective 3
To estimate the other benefits using the real-time tracking system.

6. Could the collected data be used to remove using paper documents?
7. What is the other possible use of the data?

Together these objectives aim to give new information for developing the excavating and mass hauling process for E.M. Pekkinen Oy. These research objectives are selected to gain information on using the real-time tracking system for future infrastructure projects. The objectives are selected for different purposes.

The first objective is to design new model for optimizing excavation and mass hauling process utilizing real-time tracking system. Current mass haul optimization techniques do not consider real-time information. In order to achieve full potential of real-time tracking solutions excavation and mass hauling process needs to be redesigned too. Research questions are selected to answer what the optimal model is and what is its benefits. These results help to utilize real-time tracking systems in future projects for their full potential and evaluate when utilization of the system is reasonable. Real-time tracking systems require purchasing license for the software, providing proper tools for users and educating the staff. The benefits of the real-time tracking system with new processes need to be larger than sum of these costs.

The second objective is to identify areas with potential for improvement in excavation and mass hauling process and make control actions to improve performance. This objective is selected to investigate what can be improved with or without the use of the real-time tracking system in the future projects. Research question are selected to answer what potential improvement areas are, how they can be improved and what is the benefit of doing so. Real-time tracking system might not be reasonable to be used in every project. Therefore, these results help to improve excavation and mass hauling process in all projects even if real-time tracking is not used. Results also help to utilize a real-time tracking system for its full potential as these improvement areas are recognized and can be considered in future projects where real-time tracking system is used.

The third objective is to estimate other benefits using the real-time tracking system. This objective is selected to estimate if there are other benefits that are not visible in one construction project and that might affect indirectly to costs or durations of a project or a process related to it. Research questions are selected to answer if paper documents can be removed and estimate other potential use of the data. Results of these questions help to estimate when utilization of the system is reasonable what other processes could be developed using the real-time tracking system.

1.3 Research Method

The research method of this study is Design science research (DSR). In design science research the focus is on creating of a functional solution to solve a relevant and important problem (Geerts, 2011). The created artifact can also be a more effective way to operate. Many fields have adopted the use of design science research and it is widely used among engineers and artists. Design science research methodology was chosen for this thesis because it is characteristics:

> *"DSR, which is centred towards practical problem solving, includes prescriptive or solution-oriented knowledge where the result from scientific justification (predicting, understanding or explaining phenomena) can be used in designing solutions to complex and relevant field problems. It is rather field-problem driven and solution-oriented with a core mission to develop knowledge that can be used by professionals in the field in question to design solutions to their field problem by describing and analysing alternative courses of action in dealing with field problems."* (Hanid, 2014, p.4)

Design science research methodology includes six tasks: problem identification and motivation, definition of the objectives for a solution, design and development, demonstration, evaluation and communication (Peffers et al. 2008). Geerts (2011) describes these activities as following:

1. *Problem identification and motivation.* Purpose is to determine the specific research problem. Because problem definition will be used to develop an artifact that provides solution to the problem, it justifies the value of a solution which motivates the researcher and the audience.

2. *Define the objectives for a solution*. Purpose is to infer objectives for the solution and gather knowledge that is possible and feasible for the solution.
3. *Design and development.* Purpose is to design and develop an artifact which solves specific scientific problem. An Artifact can be new constructs, altered models of existing ones or new methods that solve the problem.
4. *Demonstration.* Purpose is to prove that created artifact functions for the designed purpose.
5. *Evaluation*. Purpose is to measure the effectiveness of the artifact by comparing objectives and results.
6. *Communication*. Purpose is to share knowledge for the researchers about the scientific problem and designed solution, effectiveness of the solution, and its utility. (Geerts, 2011)

This thesis consists of a literature review, empirical research, solution proposal, results, conclusions and proposals for further studies. The literature review displays the existing situation of the excavation and mass hauling process, existing earthwork optimization methods and real-time tracking solutions and experiments. The empirical research consists of a field experiment to test real-time tracking of mass hauls in infrastructure construction project.

Scientific articles were searched from Scopus to get reliable references. Scopus allowed access to “Science Direct”, “ASCE library”, “Taylor & Francis”, “ResearchGate” and “ProQuest”. Also, academic journals such as “Automation in Construction”, “Construction Management and Economics” and “Journal of Information Technology in Construction” and “Lean Construction Management” were used.

1.4 Research Framework

In this section the research framework is described. Sections of this thesis and design sciences process advances alongside. The relationship between research framework and design sciences process and research objectives are presented in Figure 3.

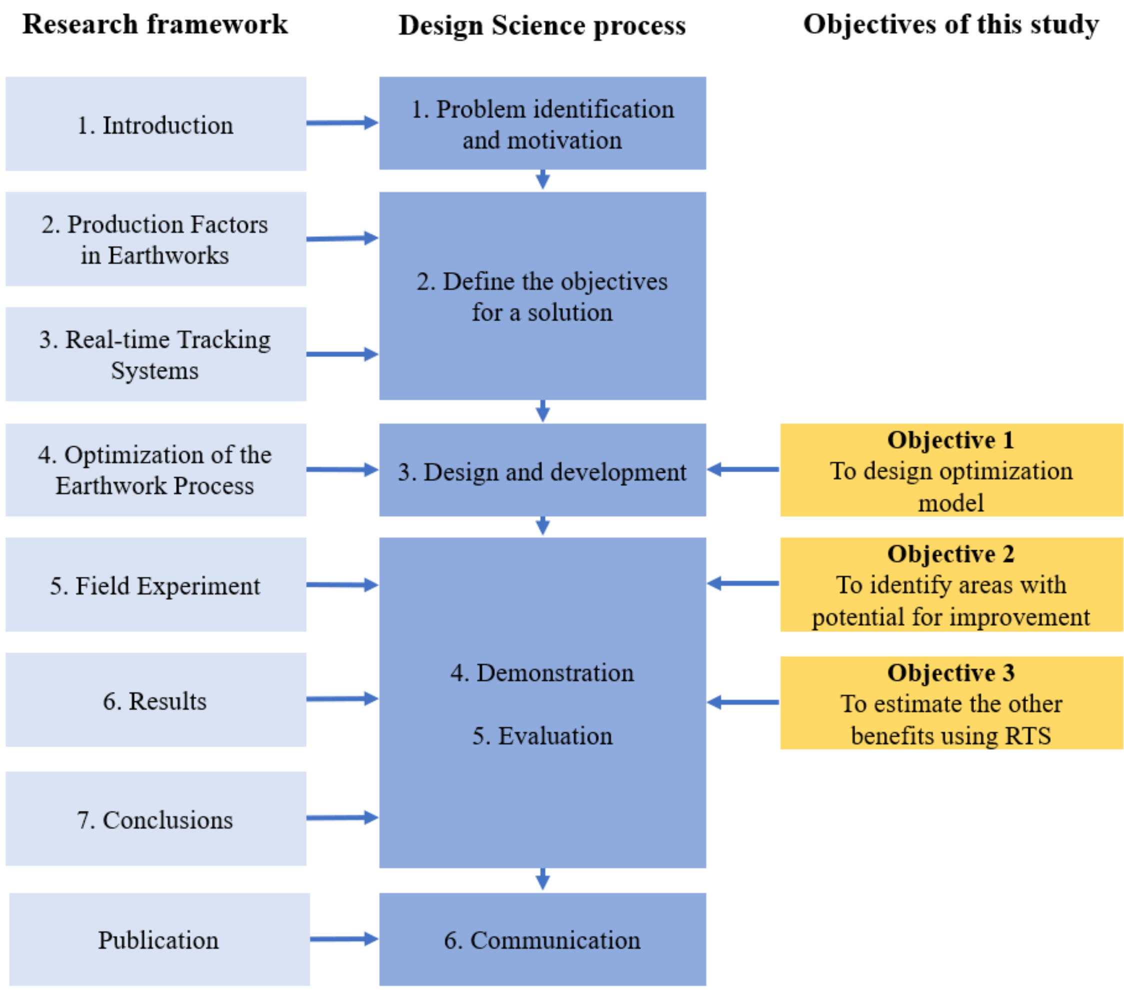


Figure 3. Research framework along with Design Science process and Objectives.

As Figure 3 shows purpose for the objective 1 is to design and development of new optimization model (=artifact) for earthwork process. The second objective aims to identify potential improvement areas in field experiment by demonstrative methods and evaluate their cost reducing potential and potential control actions. Third objective aims to estimate other benefits using real-time tracking system than what were identified in objective 2.

The paper is organized as follows. Section 2 provides overview to production factors in earthworks. The real-time tracking technologies and previous experiments are presented in Section 3. New optimization method for excavation and mass hauling is presented in Section 4. Field experiment for the real-time tracking of mass hauls is presented in Section 5. Results are shown in Section 6. In Section 7, conclusions and suggestions for future researches are discussed. References are in Section 8.

2 Production Factors in Earthworks

2.1 Analysis of Earthwork Production

In this section theoretical framework for earthwork production system is described to understand what the earthwork process is and what is its current state. Any production system can be viewed as an input-output system (Starr, 1966). There are set of resources that are transformed into another set. Starting resources can be viewed as input and the final state of resources as output. This process of transformation can be called as Production. (Grubbström, 1995). Figure 4 shows illustration of this model.

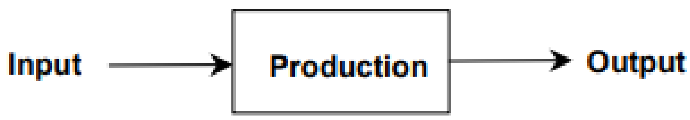


Figure 4. "Production is the transformation of one set of resources into a second set" (Grubbström, 1995, p.1)

Construction production consists of transforming machines, labor and materials (input) into desired structures and products (output). According to Koskela (2000), production process can be decomposed into smaller subprocesses, which are also part of the transformation process. Decomposing process into subprocesses makes this overall production more manageable. Figure 5 shows this decomposition of the process into subprocesses.

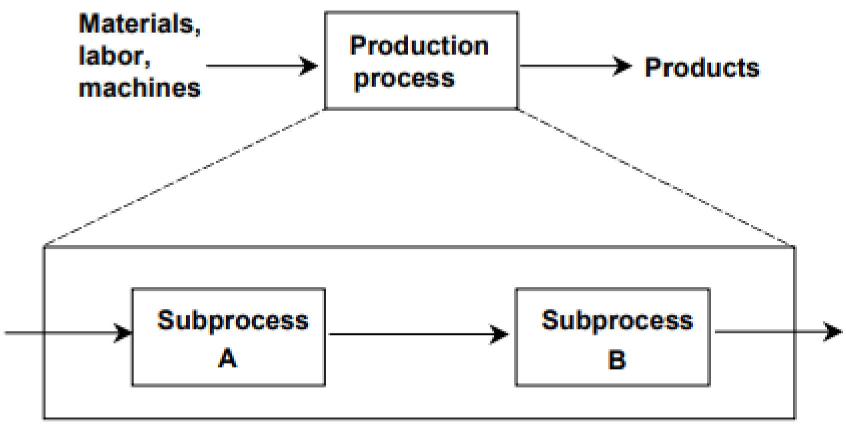


Figure 5. Production process divided hierarchically into subprocesses (Koskela, 2000, p. 42)

Number of subprocesses depends on the scope of the construction project and project characteristics. Each subprocess include its own requirements for pre-product, different set of resources (material, labor and machines) and produce a product that is closer to the final product. These smaller subsystems interact with each other according to a certain organization. Production process and its subsystems are subjected to different time- and place-dependent extrinsic influences. (Kirchbach et al. 2012). Figure 6 shows production system with these influences.

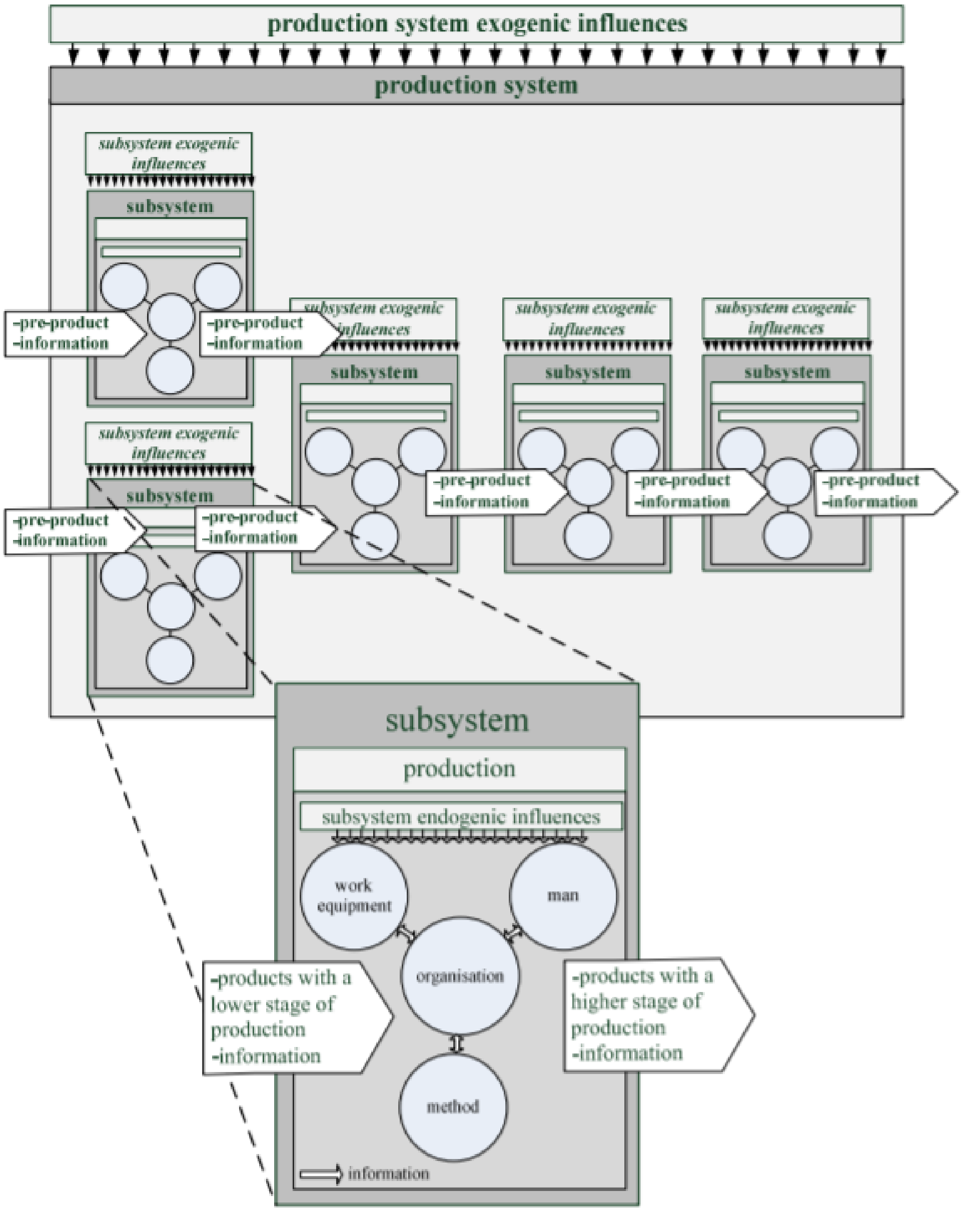


Figure 4. Interpretation of the production system (Kirchbach et al. 2012, p.2).

The production system is affected to two different kind of influences, production system exogenic influences (e.g. political and environmental influences) and intrinsic influences (e.g. subsystems endogenic and exogenic influences). Subsystems endogenic influences such as machines, labor, materials, organization and information can cause exogenic influences to other subsystems. (Kirchbach et al. 2012).

The overall production cost is the sum cost of its subprocesses. According to Koskela (2000, p.42) "the cost of the total process can be minimized by minimizing the cost of each subprocess". In each subprocess time is consumed for either transformation activities or non-transformation activities (Gilbreth, 1922). Transformation activities can be called as value-adding activities if they are necessary for creation of the final product. Unnecessary activities can be called as non-value adding activities or waste. The flow concept of the production means that these non-value-adding activities are minimized. (Koskela, 2000). Figure 5 shows production as a flow process.

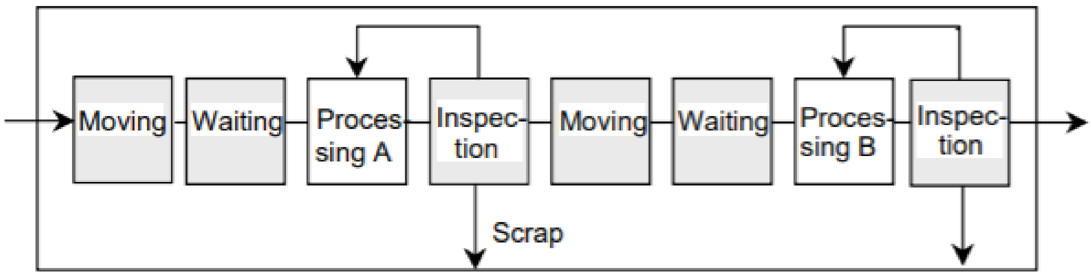


Figure 5. Production as a flow process. The white boxes represent value-adding activities and others are non-value-adding activities. (Koskela, 2000, p56).

As the figure 5 shows only Processing activities A and B move product closer to its final state. All other steps are non-value-adding activities that can be removed or minimized in order to improve production flow. There can be different types of non-value-adding activities. Ohno (1998) stated that waste can result from different sources that influence to flow such as:

- *"Waste of overproduction*
- *Waste of correction*
- *Waste of material movement*
- *Waste of processing*
- *Waste of inventory*
- *Waste of waiting*
- *Waste of motion"* (Koskela, 2000, p.57).

According to Monden (1994), waste can be excessive production resources, overproduction, excessive inventory and unnecessary capital investment. Waste can occur due to endogenic or exogenic influences of the production process (Kirchbach et al. 2012). Koskela (2000) states that waste can be reduced by minimizing lead time and variability of the production. The lead time includes time consumed for processing, inspection, waiting and moving. Reducing non-value-adding activities obviously reduces lead time. Lead time may increase due to variability of the processing activities, inspection, waiting and moving. Thus, reducing variability also reduces lead time. Variability can be reduced locating sources of variability and trying to minimize their impact (=continuous improvement). (Koskela, 2000). Figure 6 shows interpretation of reducing lead time by removing waste.

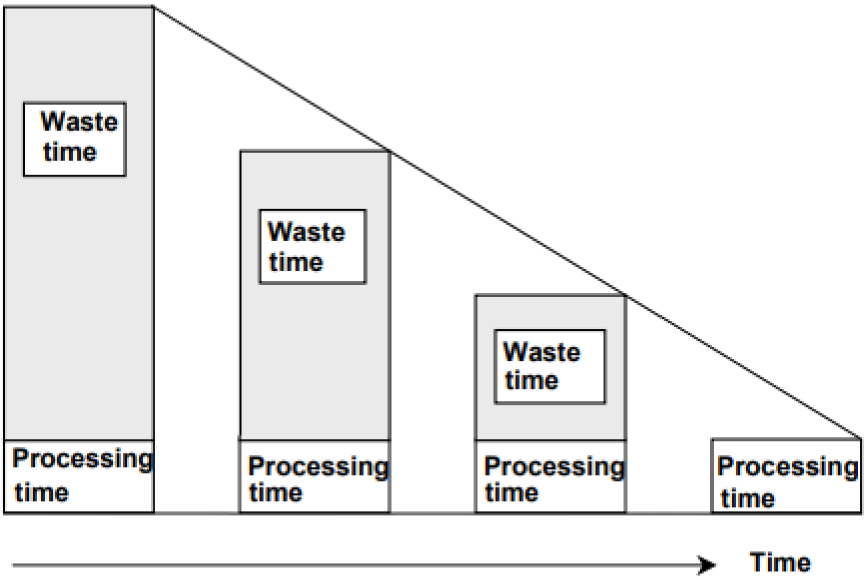


Figure 6. Elimination of waste and variability reduces lead time of a process (Berliner and Brimson, 1988).

Earthworks can be considered as a subprocess of the production process. The production process can be building construction project or infrastructure construction project (e.g. road, railway or bridge construction). First objective of this thesis is focusing on the development of this subprocess using real-time tracking system. Second objective focuses on continuous improvement aspect, reducing the waste from the subprocess. Third objective focuses on how this subprocess with real-time tracking systems' influences on other subprocesses. All objectives aim to reduce waste from the production and thus reduce lead time and increase productivity. Figure 7 shows how objectives place along the production system.

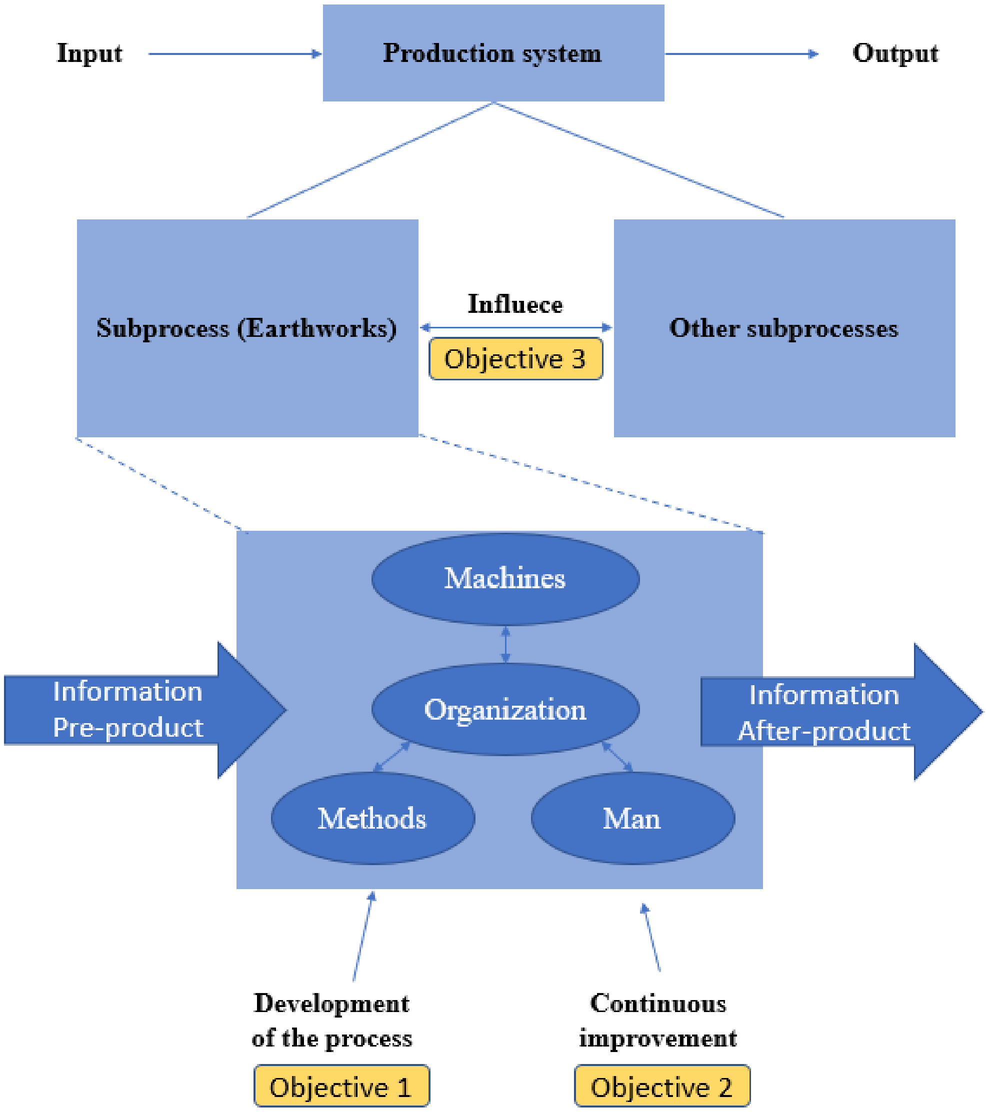


Figure 7. Illustration of the objectives and production system.

2.2 Excavation and Mass Hauling Process

In this section, earthwork process is described. The process is called as excavation and mass hauling process as its more descriptive word for the earthwork process. As previously mentioned, this subprocess is part of the production system that can be building construction project or infrastructure construction project. The process consists of consecutive activities with different earthwork equipment. Activity areas are excavation front, hauling material to the compaction front and return trip back to excavation front. (Parente et al. 2015). Figure 8. shows excavation and compaction fronts aligned with earthwork equipment.

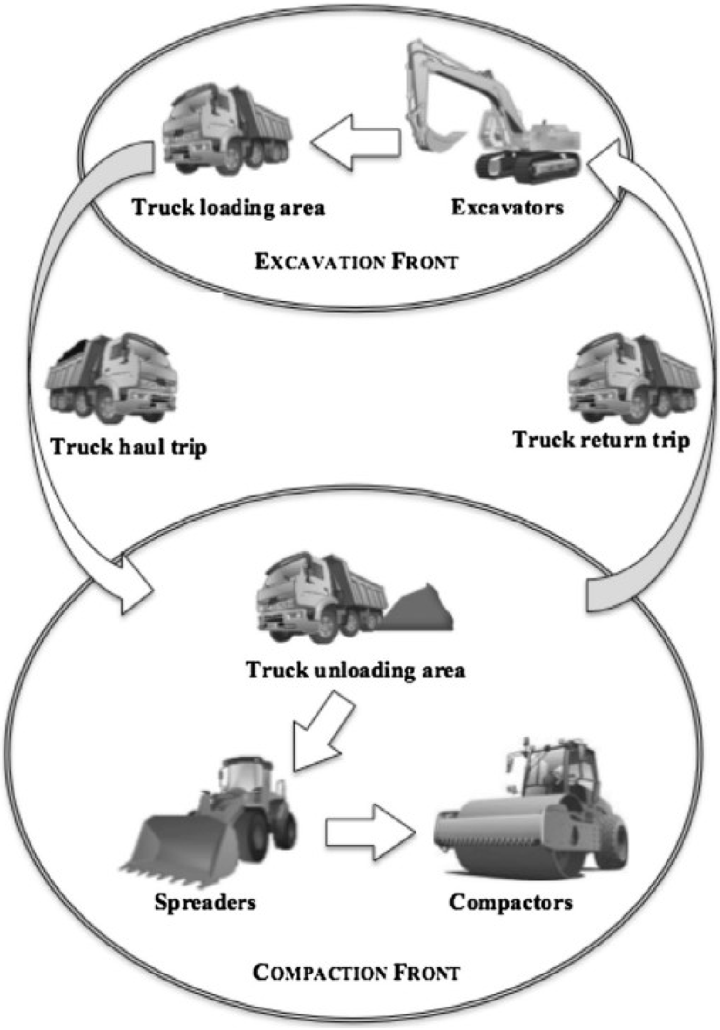


Figure 8. Excavation and compaction fronts aligned with earthwork equipment (Parente et al. 2015, p6676).

Cycle starts when excavator cuts the soil and loads it to the truck at the excavation front. Loaded mass is then hauled into compaction front to be unloaded. After unloading, truck returns to loading area and unloaded material is spread and compacted with different equipment. Performance and number of the machines are important factors in designing the process to flow smoothly. Excavator needs to be able to cut and load material into truck in suitable time. Larger excavator results shorter loading times but increase maintenance costs.

Trucks have different carrying capacities and maximum travel speeds depending on their model. Dumper can be also used to haul material. Dumpers are used mainly in in-site mass hauling and they can carry larger volumes, but they are not allowed to drive in public roads. Trucks can be used to haul material in public roads but are therefore restrained to lower carrying capacities.

The longer the hauling distance between excavation and compacting front is the more trucks are required for the flow to be optimal. The optimal flow means that waste is minimized from the process. Too many trucks will cause crowding of the trucks (=waste of waiting). Crowding can occur in both fronts. Thus, work rate of the excavators and compactors should be designed to be close to each other. It is important to optimize all available resources in terms of cost and duration. Too low number of trucks will cause excavator and compactor to wait. Minimizing waiting time cannot be achieved at the expense of a lower utilization of capacity resources. Poor utilization of the machines is also waste (=excessive production resources).

Excavation and mass hauling process is suspected to other varying factors such as human errors, operator efficiency, varying soil, varying traffic and weather conditions. Also, the large number of possible earthwork equipment allocation combination make the optimization a complex task. Excavation and mass hauling process is performing at its full potential when waste is minimized from the process. This means that all the activities in the process occur fluently.

2.3 Potential for Improvement

Earthwork activities have currently large potential for improvement. Potential for improvement means that there are non-value-adding activities (=waste) happening that could be reduced. Earthworks can be considered logistics in nature as they include moving soil material either to or from the construction site. Soil material can be moved also inside the different parts of the construction site. Construction logistics has been subjected to several researches.

In building construction projects significant share of the total costs are formed from logistics costs. Wegelius-Lehtonen (2001) studied logistics costs for materials delivered to building construction site in eight different supply chains. For one of studied supply chains the logistics costs exceeded 60% of the purchase price. For two other studied supply chains Figure exceeded 25% and remaining ones were over 10%. Fellows et al. (2002) estimated that materials account between 30 to over 50% of the total costs of a building project. Material costs includes cost of raw material and their transport to the construction site. Coyle et al. (2003) estimated that transportation costs present approximately 39 to 58% of the total logistics costs. Therefore, transportation costs represent great amount of the total costs of the construction industry. Thus, improving earthworks performance can have notable impact on building construction projects productivity.

Infrastructure construction projects logistics has also been found to be a promising area to improve productivity (Kirchbach et al. 2014). According to Miao et al. (2011), earthworks activities often incur the largest share of total costs and durations in railway and road construction projects. Thus, proper managing of the earthworks has major impact on total costs of infrastructural construction project. Earthworks usually require the use of heavy machinery. Although the earthwork machines are expensive, it is peculiar that equipment’s are not utilized at their full capacity. Kaiser and Zikas (2009) analysis estimated that trucks were standing idle approximately 50% of their cycle time. Parente et al. (2015) estimated that optimal equipment allocation use could potentially reduce costs and durations of a construction phase from 20% to 50%.

2.4 Earthwork Optimization Approaches

Improving earthwork activities can have notable impact on both building and infrastructure construction projects productivity. This might be reason why earthwork optimization has been subjected to several researches. Although many of these different methods are not considered suitable as earthworks optimization include special characteristics. Metaheuristics offers promising solutions for optimizing the earthworks, such as genetic algorithms (e.g. Xu et al. 2011) and swarm intelligence (e.g. Nassar and Hosny 2012). However, most of these studies target only partial processes or tasks that earthworks include. Therefore, these solutions lack the benefits of total optimization of costs and duration in all construction phases.

Parente et al. (2015) presented Evolutionary Multi-objective Optimization approach that includes optimization of both costs and durations in all earthwork construction phases. The study states that earthworks can be interpreted as series of production lines. Construction phase can include multiple production lines at the same time if there are enough machines to enable it. Figure 9. shows the algorithmic flow of dynamic earthwork resource allocation.

Figure 9. Algorithmic flow of dynamic earthwork resource allocation (Parente et al. 2015, p6677).

This resource allocation considers maximum efficiency of the equipment and minimization of the total construction time and costs. Construction costs and durations of each phase can be calculated subsequently. Maximizing the work rate of the last task in these production lines will result highest global productivity. Considering that compaction is the last activity in production line, it sets the optimal work rate for the whole system. Maximizing the work rate of compaction sets work rates that spreaders should be able to handle. Same optimal work rate is continued for transportation and for excavation equipment's. Knowing the work rates for different equipment enables to allocate proper number of suitable equipment for each activity. Evolutionary multi-objective optimization method uses computational methods to maintain population of potential resource allocations with chromosomes denoting individual data presentation of a solution. Large number of possible solutions are computed to find out the most optimal resource allocation. (Parente et al. 2015)

Since major number of existing earthwork optimization methods tends to focus on the prediction of the equipment work rate rather than actual performance, there are not valid methods if working conditions change too much. Although EMO model presented by Parente et al. (2015) optimizes the resource allocation, it lacks the quick reaction to varying conditions. The model suggests progress data obtained from compaction front to be saved and used when determining the compaction duration for the next construction phase. In longer construction phases this creates waste if designed work rates are not achieved.

Variation in work rate can be caused by the factors such as, operator skills of the excavators and truck drivers, personal delays, traffic delays, varying material and weather conditions. It is highly probable that work rate is not constant value during the whole construction phase, instead it variates because of so many uncertainties and variabilities. Kirchback (2014, p.665) declares that "adaptation to current situation does not take place". Earthwork optimization system should utilize real-time information on actual work rate in order to provide reliable data as a basis for the optimal design.

Actual work rates of different excavator types might be same depending on the operator, even though another excavator should have bigger performance capacity value in guide sheets. Also, work rate of the trucks varies depending on route decisions, how full they are loaded and material parameters of the hauled mass. Heyl (2015) recognizes that performance of trucks is empirical value and that cycle time should be determined in trials for each situation. Only by measuring the actual work rate it is possible to design equipment allocation that takes all the variabilities into consideration. Complex projects and urban environments require quick reaction to changes. Sobotka and Blajer (2017) noticed in their case study on earthwork logistics in the high-density urban condition that success of a project depends on quick reactions to changes.

Monitoring of the performance of the logistics should be performed in order to develop it (Sillanpää 2015). Modern tracking systems provide fascinating possibilities to collect data in real-time. Furthermore, only by measuring the performance in real-time it is possible to identify uncompetitive management practices (Ying and Tookey 2017).

Kirchback et al. (2014) introduced digital Kanban, real-time monitoring control center for earthworks. Methodology is realization of digital Kanban cards with technological tools. In digital Kanban, information is shared between earthwork equipment and control center. Figure 10 shows information flow using information technology. Approach focuses on collecting data on actual performance and using intelligence to detect abnormal conditions, provide suggestions for improvement and allow construction manager to interfere and decide on suggestions and on changes. Kanban cards tries to prioritize according to expected performance and prefers using excavators and dumpers that can-do higher performance.

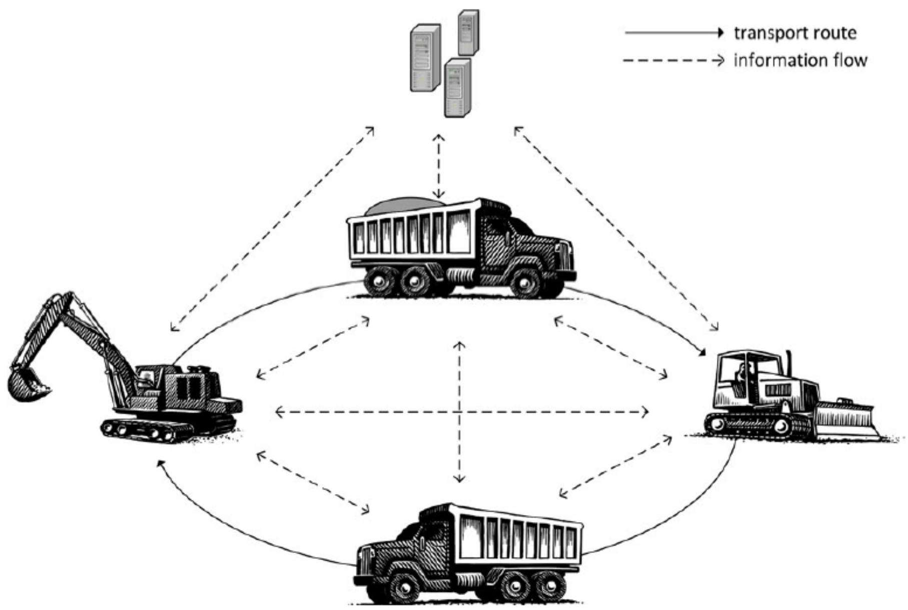


Figure 10. Information flow using information technology (Kirchback et al. 2014 p668).

However, information technologies presented in Figure 4, have not yet been introduced to active use for construction sites. Although, method seems to be very promising as it takes actual performance as a basis for designing the optimal earthwork process. However, it is missing the compaction tasks, which is in many cases the last activity. Performance of the whole production line cannot be designed if some of the tasks are missing. Digital Kanban also misses the logic of designing the equipment allocation according the last task of the production line.

3 Real-time Tracking Systems

3.1 Technological Solutions

The constructive industry has not yet been seen widely utilizing information technologies for automatized data collection, instead industry relies largely on manual data collection methods (Jiang et al. 2012). This might be reason why earthwork optimization methods have not evolved as much as they could have. It is important to understand advances in technology to be able to optimize earthwork process better. For that reason, real-time tracking systems are described in this section.

Real-time tracking technologies enhance information flow in production system. Information flow is important part of each subprocess as organization does all the control actions based on available information. Information gathered by the system can help project managers to improve quality control, logistics and safety of the construction site (Constin et al. 2015). Construction projects usually produce large number of information that is traditionally gathered and analyzed manually. In addition to manual data collection being inaccurate and insufficient (Jiang et al. 2012), it is prone to human error (Costin et al. 2012) and the data is received too late (Navon and Shpatnitsky, 2005). Thus, construction industry has been seen to benefit from automatized data-collection methods (Pradhanaga and Teizer 2013).

Zhai etl al. (2009) studied the connection between labor productivity and integration of construction information systems and concluded a positive interaction between these two. These projects with higher use of technological solutions resulted improvement of 31 to 45% in productivity. Beck and Bell (1995) calculated that using fully electronical data management technologies in material management with reengineered processes 85% time savings and 75% cost savings could be obtained.

Researchers in construction industry have introduced real-time tracking systems utilizing different technologies such as radio frequency identification (RFID) (e.g. Song et al. 2006), ultra wideband (UWB) (e.g. Cheng et al. 2011), global positioning system (GPS) (e.g. Grau et al. 2009), multiple sensors (e.g. Razavi and Haas 2010) and bluetooth low energy (BLE) (e.g. Olivieri et al. 2017). Technologies have been shown to be successful in inventory management, asset tracking, improving safety and productivity (Cheng et al. 2011, Kelm et al. 2013).

Suitability of different technological solutions depends on the construction project and on its characteristics. RFID, UWB and BLE based systems require pre-installed readers in known locations to identify the location of the resources. These are suitable solutions for building construction projects where same locations are continuously being used by different work crews. Building projects also have suitable infrastructure for the systems, as different locations in the building have usually electricity available.

Infrastructure construction project locations are usually vast in nature and same activities are conducted for longer distances, thus they are not ideal for using pre-installed components. Instead, larger construction projects resources can be tracked with GPS based real-time tracking systems with reasonable accuracy and costs (Pradhananga and Teizer, 2013). GPS utilizes triangulation information from orbiting satellites to determine a three-dimensional position (Carlos, 2006).

3.2 Previous Experiments

Earthworks can be considered logistics in nature as they include moving soil material. It is well accepted that real-time tracking systems can be used for material tracking. Material management with real-time tracking systems decrease time used for finding materials and reduce number of missing items. Caldas et al. (2006) used GPS devices in material management and noticed that average time spend locating a material decreased from 6 minute 42 second to only 55 second. Grau et. al. (2009) estimated that real-time tracking systems could potentially reduce time used for material tracking in a construction project from 36,8 min to 4,56 min and could potentially save $121 507. Demiralp et al. (2012) estimated that material management with RFID technology could reduce total costs by 3,1%.

Although many of the researchers have studied real-time tracking systems only very few systems have been implemented fully in real construction projects (Li et al. 2016). Constin et al. (2015) studied worker location tracking with RFID tags in a large hospital construction project and observed improved safety and security, improved quality, more effective workforce and improved billing and record keeping. Zhao et al. (2017) studied real-time resource tracking implementation practices and use cases in Finland, China and Brazil and suggested real-time tracking system to enhance productivity and decrease time wasted for nonproductive activities.

Previous examples are from building construction projects, although positive benefits have been also achieved in infrastructure construction projects. As previously mentioned, GPS based real-time tracking systems are better for earthwork application (Pradhananga and Teizer, 2013). Thus, all these researches with different technologies might not produce similar results in infrastructure project since they have different project characteristics. GPS based tracking system used in construction site in New Zealand have been shown to increase effective working hours of construction equipment and reduce construction duration (Li et. al. 2005). GPS based real-time tracking applications have been in use in Dam construction project in China where it was used to provide accurate information for labor consumption purpose (Jiang et al. 2015).

However, while studies have identified real-time tracking systems to have some benefits when used in real construction projects, practical issues involved with it have been little to no focus. This has been identified also in literature study where different real-time tracking related articles were examined. In this study Li et al. (2016, p.45) states that “little is known of the practical issues involved in implementation, such as deployment time, cost, and decrease in accuracy of the system due to noise, time taken etc.”

Previous researches with real-time tracking field experiments do not help determining when to utilize real-time tracking system. There is need for more implementations of the real-time tracking systems in different projects.

4 Optimization of the Earthwork Process

4.1 Proposed System

As shown previously, current earthwork optimization methods lack the agile adaptation to actual situation. Recent advances in real-time tracking systems provide new possibilities to optimization of the earthwork process. In this section, new Agile Earthwork Optimization (AEO) method is presented as a creation of this thesis. AEO method relies on adaptation to current situation using actual progress data provided by real-time tracking system.

Agile Earthwork Optimization is combination of the models developed by Parente et al (2015) and Kirchback et al. (2014). According to Parente, performance of the global system should be designed according to the performance of the last task in production line which is compaction. However, this model predicts the optimal allocation and does not adapt well to current situation. It is essential to add real-time data (e.g. loading configurations, cycle times) to this system in order to be able to be agile and add flexibility to changing conditions. Variation in the process creates waste and decrease the productivity. When considering that excavation equipment and trucks have rarely the same performance as they have in guide sheets, it is reasonable to evaluate optimal allocation daily. Measuring can help to determine reasons for capacity downgrades. Improving utilization of the excavation and mass hauling equipment daily adds value to the earthwork process and decreases unproductive activities.

Digital Kanban introduced by Kirchback et al (2014), suggests using sensors and information technologies to dynamically adapt allocation of earthwork equipment. Proposed Agile Earthwork Optimization system utilizes these real-time tracking technologies along with optimal allocation methods to produce the optimal utilization of earthwork equipment. Purpose is not to design the most optimal theoretical equipment allocation, instead to utilize the used earthwork equipment for their designed potential even if changes occur. The algorithm for the Agile Earthwork Optimization system is presented in Figure 11.

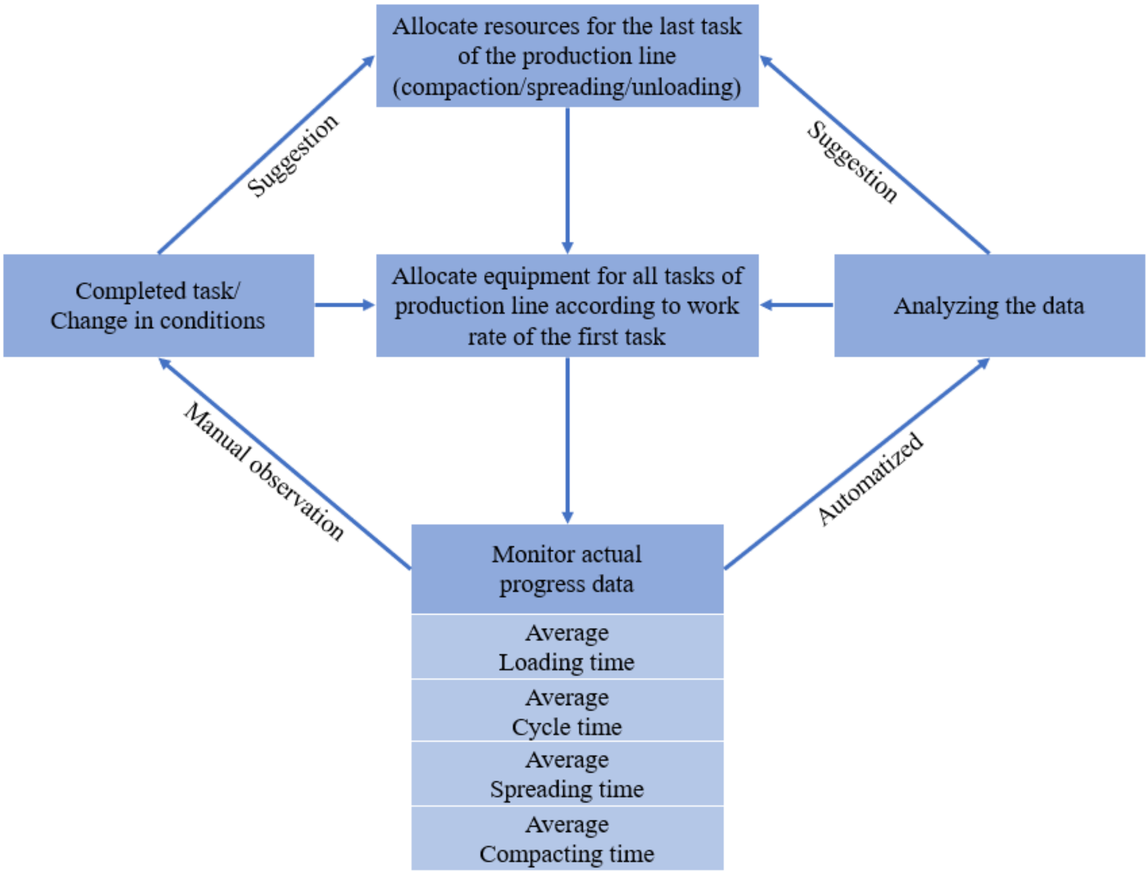


Figure 11. Algorithm for Agile Earthwork Optimization method.

As Figure 11 shows, first resources are allocated to the last task of production line which can be compaction, spreading or unloading. When designing the optimal equipment allocation for each situation, dependencies of the excavation and compaction fronts should be evaluated. In many cases, these two fronts are parallel activities and are not affecting to another's performance. Such case is presented in following section in which real-time tracking of mass hauls is tested in a real construction case. In this case the last production line is unloading the material to compaction front. Thus, performance of the compaction does not affect to the performance of the excavation front. Unloading tasks are restricted by limited hours the land pit is open. Such situations are common for infrastructure construction projects located in high density urban areas with limited working spaces and limited amount of land pits. Land pit open hours sets the required work rate of the global system. The maximum unloading time depends on the loading capacity of the excavator and cycle times of the trucks.

4.2 Steps

Allocation of transportation and excavation equipment is first designed according to construction manager's experience or using actual performance information from previous projects. Then actual performance is monitored using real-time tracking system. Depending on the situation different values are monitored. For example, considering that unloading of the truck is the last task of the production line, only average loading time and average cycle time is needed to be monitored as production line does not include spreading or compacting activities. In such case, if excavator has average loading time of 12 minutes and average cycle time for trucks is 48 minutes, it can be calculated that maximum loading capacity is with 5 trucks per excavator, as excavator has 48 minutes to load 4 truck after loading the first one. Using actual progress data from the excavation and mass hauling process it is possible to calculate the utilization rate of the excavator and trucks and evaluate proper adjustment daily. If excavator is not utilized for its full potential, more trucks can be assigned. Also, if crowding of the trucks occurs (e.g. which will result growth of cycle times and decrease number of hauls per truck) suitable number of trucks can be reduced, higher performing excavator can be assigned, or other control actions can be executed. The benefit of the method is that unprofitable behavior can be recognized early and minimized. Even if changes occur (e.g. material changes, different operators, traffic, different routes), method can reallocate equipment to adapt to that situation.

The method has two ways to make changes to the allocation. One that uses intelligent programming to automatically analyze data to make suggestions based on either statistical modelling or data from last projects (where such system have been used). Automatized real-time tracking utilization analysis have already shown to be successful in road construction project in South Korea, where Lee et al. (2018) estimated that automatized utilization analysis algorithm error was just 3,2% in excavator and from 8,5% to 12% in trucks. The allocation is also possible to be changed using manual observations from construction site such as unfinished prerequisite works, unforeseen delays and conditions. Automatized programming might not be able to take these things into account so manual observations are essential to include all factors affecting to process. This is also why the method provides suggestions that Site Manager either agrees or declines.

To prove the utility of the proposed system, Agile Earthwork Optimization method is simulated using data gathered from real-time tracking of mass hauls in infrastructure construction site. Next section, Section 5 introduces the field experiment. Simulation is presented in Section 6 results.

5 Field Experiment

5.1 Test Situation

To answer research objectives of this study and to demonstrate and evaluate the current state of the process a field experiment was executed in a real construction project with real-time tracking system. Information gathered from the field experiment is used as basis for simulation of the designed earthwork optimization method. Information is also used for continuous developing of the earthwork process and to evaluation of other potential benefits that the system could provide. Test situation is described in this section.

The application for real-time tracking of mass hauls was tested in Vaakunatori Pile Slab Construction project in Espoo, Finland. General contractor of the project was E.M. Pekkinen Oy. The construction project included excavation of an old parking site, piling, reinforced concrete pile slab foundation and crushed rock filling. The parking site before the construction project is shown in the Picture 1. The test period for the real-time tracking system was during the excavation phase of the construction site. Overview of the construction site is presented in the Figure 12. Size of the site was approximately 51m by 42m.

Picture 1. Parking site before pile slab construction project.

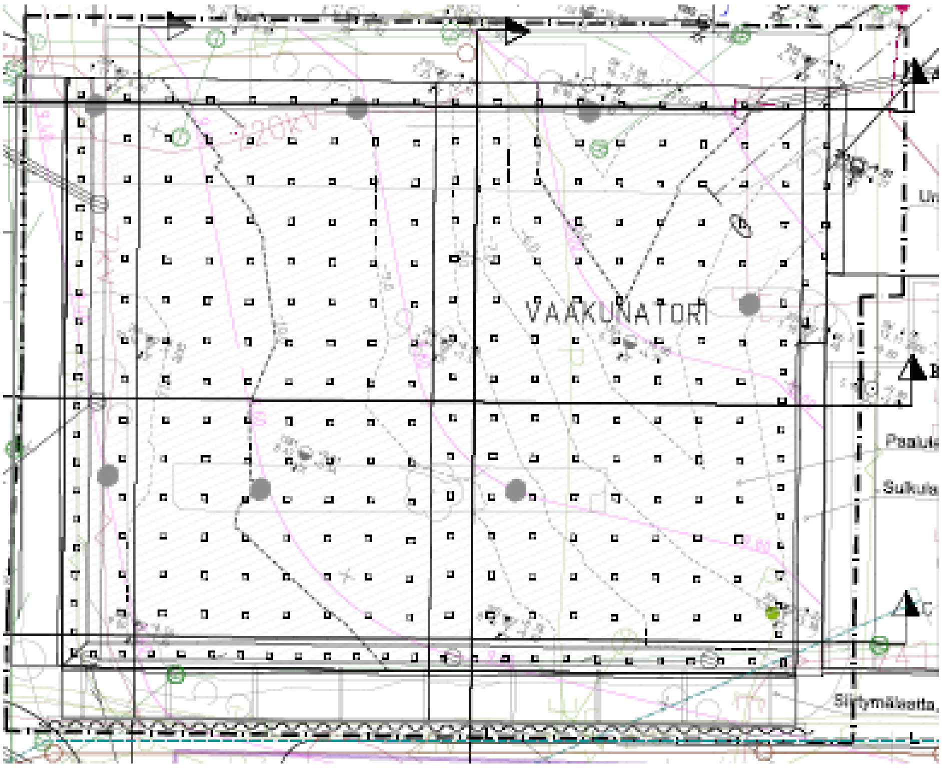


Figure 12. Overview of the Vaakunatori Pile Slab project.

In this project subcontractors Doosan 25-ton excavator was used to excavate the soil. Excavator and its operator were selected by the Site Manager based on experience. Selection was limited by the availability of different type of machines and their operators. Excavation and mass hauling phase started 4th of October 2018 and lasted until 24th of October 2018. Between this time there were 15 working days. Picture 2 shows excavation phase in progress.

Picture 2. Excavation in progress on 16.10.2018.

Excavation process included removing thin crushed rock layer on the ground surface to a level excavated earlier in the project and excavating and hauling the clay layer. Crushed rock layer was used in-site to make a working platform for a piling machine. Smaller excavator was used simultaneously to level the crushed rock layer. Leveling and compacting of the crushed rock layer did not affect on the excavation front as excavation progressed to same direction. In total six different trucks were used during excavation phase to haul material to land pit that was provided by the client. Land pit was located approximately 8 km away from the site.

Trucks consisted of a 4-axle truck with $13m^3$ volume capacity and 5-axle trucks with $15\text{-}17m^3$ volume capacities. At maximum five trucks were in use simultaneously. At the beginning of the project small amounts of asphalt, curbs, trees and stones were hauled from surface layers to different unloading areas. Main hauled material should have been stabilized clay, instead it was quickly realized to be normal soft clay. This did not affect to the location of the land pit as it accepted both materials.

5.2 Restrictions

Normal working day for the excavator and trucks were from 7.00 until 15.30 excluding Friday when the day ended at 13.30. The excavator driver took 15 minutes coffee breaks starting at 9.00 and at 13.30. A 30 minutes lunch break were to start at 11.00. Truck drivers tried to have their same mandatory breaks as excavator driver although it was occasionally more convenient to have them at different time.

Land pit for the clay was open between Monday and Thursday from 7.30 to 16.00 excluding time between 11.30-12.00 when it was closed for lunch break. On Friday land pit was open from 7.30 to 14.15, excluding the time between 11.30-12.00. Hauled mass needed to be unloaded and the truck removed from the unloading area before the closing time. Asphalt and curbs were hauled near to clay land pit area.

Sheet pile wall were to be installed to the south-side of the construction site (as shown in Figure 12) before excavation in that area. Sheet pile walls were delivered to the site on 9th October and installed between 10th and 12th October. This restricted the starting point and the direction of the excavation embankment.

5.3 Haul Truck Application

Real-time tracking system in use was Haul Truck application by Topcon Positioning Systems. Topcon Positioning Systems manufactures precise positioning products and solutions for surveying, construction, civil engineering, BIM, asset management, and mobile control markets. The company also develops construction management software, construction field software, geospatial software, remote management tools and machine control systems.

The Haul Truck application is part of Topcon's Sitelink3D jobsite connectivity and productivity solution, providing data control, machine tracking and a reporting system. With Sitelink3D, Topcon expands its 3D machine control systems to include remote machine support, job file transfer and real-time project management information.

The Haul Truck application was installed to iOS- and Android-tablets which included SIM-cards to allow mobile internet connection and data transferring in real-time. Participating truck operators were asked to sign an informed consent form for tracking. When entering the site for the first time, each truck operator was handed randomly chosen tablet and instructed how to use the application. Picture 3 show tablet interface of the application.

Picture 3. Haul Truck user interface on Samsung Galaxy Tab Android device.

Truck operators were asked to log in to the haul truck application every day when they were ready to start. They were asked to select material of the loaded mass, select load when they started loading and select unload when they reached unloading location. This process was then continued for the duration of the work day. They were asked to log out of site when they were finished with hauls and no time was left to haul material. The application used the tablet's inbuild GPS to record their positions and send them into cloud. Tracking system recorded location points of loading and unloading, travelled routes, cycle times and distances for each operator. Using Topcon Sitelink3D web-interface data was available to be analyzed and downloaded into Excel form if needed. Also, web-interface allowed following the trucks in map view in real-time.

The author created the construction site to Sitelink3D and set all configurations (e.g. locations, materials). Web-interface was operated by the author and information on the hauling progress was daily sent to the Site Manager. Site Manager did all decisions regarding control actions. Most of the trucks were owned and operated by subcontractors. Some control actions were gained from the Project Manager. An example of such control action was when the need to use Company's own truck occurred.

6 Results

6.1 Validity of the results

The field experiment with real-time tracking application for mass hauls resulted in a large amount of data. The data included information on date, time, machine, operator, material, quantity, unit of quantity, starting and ending locations, starting time, duration and distance of load and dump phase and overall total values for every haul. Web-based interface allowed route visualization in a map view and filtering the data with different parameters (e.g. operator, date or material). At the beginning of the field experiment data was subjected to some errors due to operators learning how to use the application. Also, some singular errors happened later in the experiment. Nevertheless, most of the data was assumed to be correct. This was quantified with manual observations at the construction site. Errors in the data were manually identified and corrected to the used calculations. The most common error was forgetting to press load or unload in the mobile application at corresponding work phase, which resulted incorrect cycle times. However, this error was easily identified with the route visualization.

In total three different excavators were used during this test period. The main excavator was 25-ton Doosan which was on site for the whole test duration and had same operator all the time. The smaller excavator was used to level crushed rock when needed (not daily) by different operators and this did not affect to loading capacity of the main excavator. The third excavator 25-ton Liebherr was on site during four-day period between 9^{th} and 12^{th} October. This excavator helped seldomly with loading of the trucks. However, between 10^{th} and 12^{th} October this excavator was installing sheet pile walls and did not participate in the loading process. Thus, 9^{th} October results might have been influenced to slightly better loading time results. However, only one truck was being loaded at a time because of the construction site size restrictions during this time. Thus, influence to loading time is small. This did not influence to cycle-time durations. Picture 3 shows all the excavators in work.

Picture 3. Doosan cutting the soil, Liebherr installing the sheet pile wall and smaller excavator leveling the crushed rock on 10.10.2018. Other machines were working on the neighboring construction site.

In total 6 different trucks were used during this test period. Starting days and working durations are presented in the Figure 13. Variation in number of trucks might have caused a small variation in loading time and cycle time as different truck operators might have considered loading process to start at slightly different times (e.g. some when moving to be loaded and some when under loading). However, it is assumed that each truck operator's behavior was similar in different days so this might have generated both positive and negative errors. Thus, average cycle time and loading time values should be quite accurate.

Truck	Starting day	Days at the site	Last day at the site
1	4.10.2018	12	23.10.2018
2	5.10.2018	13	23.10.2018
3	8.10.2018	3	10.10.2018
4	9.10.2018	2	10.10.2018
5	8.10.2018	12	23.10.2018
6	11.10.2018	8	24.10.2018

Figure 13. Trucks starting days, days at the site and the last day.

Data was analyzed daily and informed to the Site Manager. This included hauled volume and average number of hauls per truck and estimated duration of the excavation and hauling phase. Analyzing the potential areas for improvement happened during and after the test period. These were also informed to the Site Manager. Some of the areas were recognized after the test period and thus were not able to be subjected to control actions.

Test period included some material surprises which caused a few haul data losses as these materials were not included in application's material list. These materials were bricks and light aggregate materials. However, manual observation helped to keep track of these hauls.

Overall data collection was quite successful. Most of the data loss happened during the first days of the test period. However, manual observations and analysis of the haul truck data allowed to keep track of the real haul numbers. Three weeks test period provided good number of data from different days and by different truck operators. Thus, data is reliable to be analyzed to find improvement areas and as a basis for the simulation.

6.2 Potential Areas for Improvement

6.2.1 Too early ending of the work shift

First identified potential area for improvement was too early ending of the truck operators' work shifts. This was recognized on day 6 (10.10.2018). Prior to these ending times were mainly correct. Time of the last haul and cycle time was checked to discover if it was possible to do additional hauls inside working time. In Figure 14 cycle times with starting times of the loading are visualized.

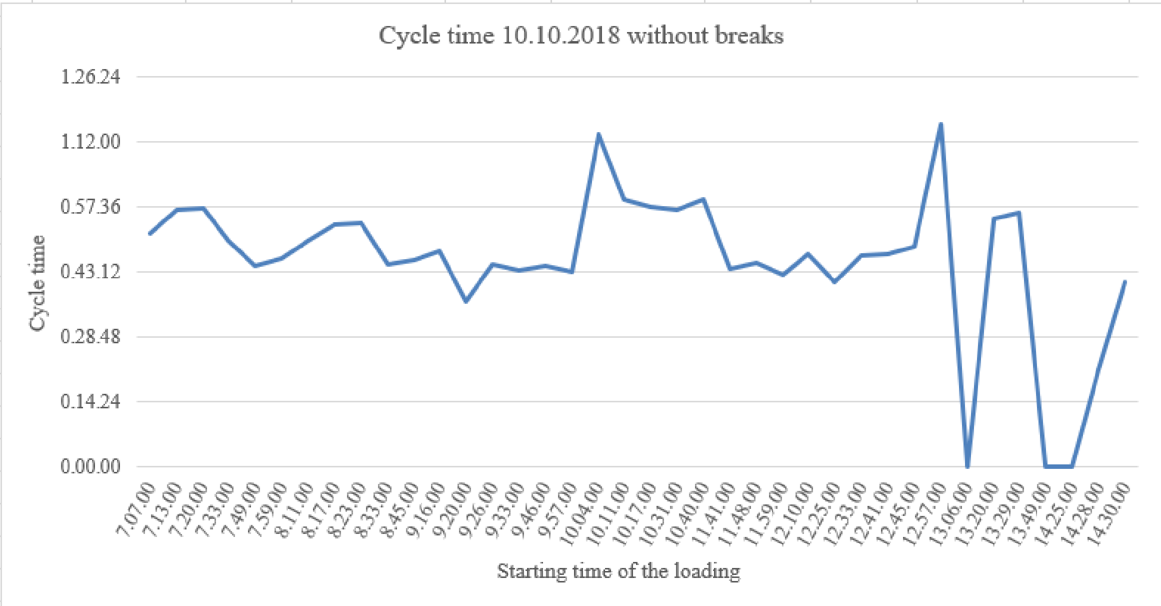


Figure 14. Cycle times with starting times of the loading from 10.10.2018. Breaks manually removed from cycle-time.

As Figure 14 shows, hauls that started loading at 13.06 and 13.49 did not finish the cycle, which means that trucks did not return to the construction site after that haul. When duration for each cycle was under 1 hour on average, both trucks could have done one more cycle. Truck operators leaving to early creates unnecessary waste for the earthwork process as excavator is not utilized fully for the whole working day. This resulted a control action. Truck operators were asked why they did not return for one more trip and they said that the excavator operator had told them that there is not enough time to come back. The excavator operator was then informed about cycle time duration and asked to change his behavior so that more hauls could be performed.

6.2.2 Route decisions

Second identified area for improvement was truck operators' route decisions. Due to large number of data this was recognized after the test phase, so control actions could not be assigned during the test. Route decisions were identified when studying why cycle times were varying between morning rush hours (7.00-9.00). As Figure 14 shows, haul that started loading at 7.59 had cycle time of 46 min and next haul starting 8.17 had cycle time of 54 min. Considering that this time period is influenced with heavy traffic, cycle time difference of 8 minutes between hauls is significant resulting in such a short distance. When looking at the route decision of these two operators it was noticed that they had selected different routes. Figure 15. shows routes of these two trucks. Blue line indicates haul trip to unloading area and red line indicates returning empty to the construction site. Blue and red arrow indicate loading and unloading points. However, lines and arrows do not match perfectly. There is a small deviation between location of the arrows and the lines. The real location for the loading and unloading points is where the line color transfers to different.

(a)

(b)

Figure 15. Truck operators' route decisions (a) and (b).

As Figure 15 shows, one truck operator drove to the land pit using roads that included highway 1. Another truck operator did not use highway 1 when driving to the land pit. Looking at more detailed information about these two operators it was noticed that (excluding one haul) these same route decisions stayed for the whole day. Figure 16 shows cycle times and distances of each haul for both truck operators during 10.10.2018. Breaks were manually reduced from the cycle times; thus, certain hauls are marked with "break not included". In addition, haul number 7 and 8 for truck 2 were estimated from the data using average values of the previous hauls. The operator did not use the haul truck app properly during these hauls which resulted that accurate information on hauls was not available. Although, from route visualization of the location data it was possible to verify that these hauls were performed using these routes. Estimates are average values of other hauls performed by that operator.

Truck 1 (a)				Truck 2 (b)			
Cycle	Time	Distance (km)	Info	Cycle	Time	Distance (km)	Info
1	0:51:44	18,590		1	0:57:17	21,526	
2	0:46:06	18,698	Break not included	2	0:53:58	21,513	Break not included
3	0:46:08	20,661	Took different route	3	0:45:03	21,501	
4	0:44:41	18,591	Break not included	4	0:59:56	21,505	Break not included
5	0:57:41	18,746		5	0:44:01	21,398	
6	0:42:39	18,578		6	0:41:02	21,437	
7	0:47:06	18,592		*7	0:50:13	21,48	Break not included
8	0:41:15	18,515	Break not included	*8	0:25:06	10,740	Only for one direction
9	0:28:16	9,397	Only for one direction	* time and distance estimated from the data			
Coffee breaks	0:30:00			Coffee breaks	0:30:00		
Lunch break	0:30:00			Lunch break	0:30:00		
Total	7:46:36	160,368		Total	7:16:36	161,100	
Mean	0:47:10	18,871	Only full cycles	Mean	0:50:13	21,480	Only full cycles

The Figure 16. Cycle time and durations of different truck operators (a) and (b).

As Figure 16 shows, route decision (a) without entering highway 1 was on average 183 seconds faster in cycle times. What is also interesting, this route was approximately 3 kilometers shorter. Truck 1 drove one more cycle during the day and still had less travelled kilometers that Truck 2. Shorter route was 6,8% faster in cycle times and had 13,4% less kilometers. Thus, it is possible to reduce time used for cycles and maintenance costs of the trucks by simply choosing the optimal route. Given that these same routes were driven for whole day it represents a good estimate on the amount that is possible to be improved.

Based on findings truck operators were asked how they chose routes. It was discovered that chosen routes are empirical decisions that are based on their previous experiences. Site Manager was then asked how he thought truck operators chose the routes. It was discovered that Site Manager thought that truck operators always choose the quickest route. Clearly there is potential for improvement in this area. In this case route selection could have been assigned by the Site Manager, although when this did not happen truck operators had to rely on their experience. This resulted unnecessary waste for the earthwork process.

6.2.3 Queuing of the trucks

Third potential area for improvement was identified to be queuing of the trucks. Queuing resulted in trucks waiting in line for their turn to be loaded or unloaded. Waiting to be loaded occurred mainly at the beginning of the day as trucks arrived at the same time at 7.00 to the construction site. For example, considering that loading time of a truck is approximately 9 minutes and five trucks were to arrive at the same time, cumulative time wasted in queuing is 90 minutes. Figure 17. shows calculation of the cumulative time wasted.

Truck		Time elapsed (min)	Waiting time (min)
1st	Instant service	9	0
2nd	Waits for the first	18	9
3rd	Waits for the first two	27	18
4th	Waits for the first three	36	27
5th	Waits all above	45	36
Total		**54**	**90**

Figure 17. Cumulative waiting time.

The actual amount of time wasted for queuing during the test is not clear as number of trucks varied quite a lot and real-time tracking system did not identify separate waiting time value for the time trucks were waiting to be served. Also, cycle-time counter for the hauls started when they were loading the first haul. Thus, information is not available how much time was wasted for waiting to be loaded the first haul. Although, based on observations conducted in construction site, previously mentioned queuing situations did occur during mornings. The loading time of the trucks was on average 8 minutes and 27 seconds for 112 clay hauls. Consecutive clay hauls were manually identified to obtain this value. Hauls did not include hauls influenced by breaks. Actual average loading time is probably a bit larger value because other than clay materials took a bit longer time to be loaded into truck. However, this also increases the time wasted for queuing.

Time wasted in queuing could be reduced by having different arriving intervals for the trucks. Although, this would require different kind of contracts. Also breaks resulted queuing. Figure 18. shows four trucks simultaneously at the unloading location that resulted because of the coffee break.

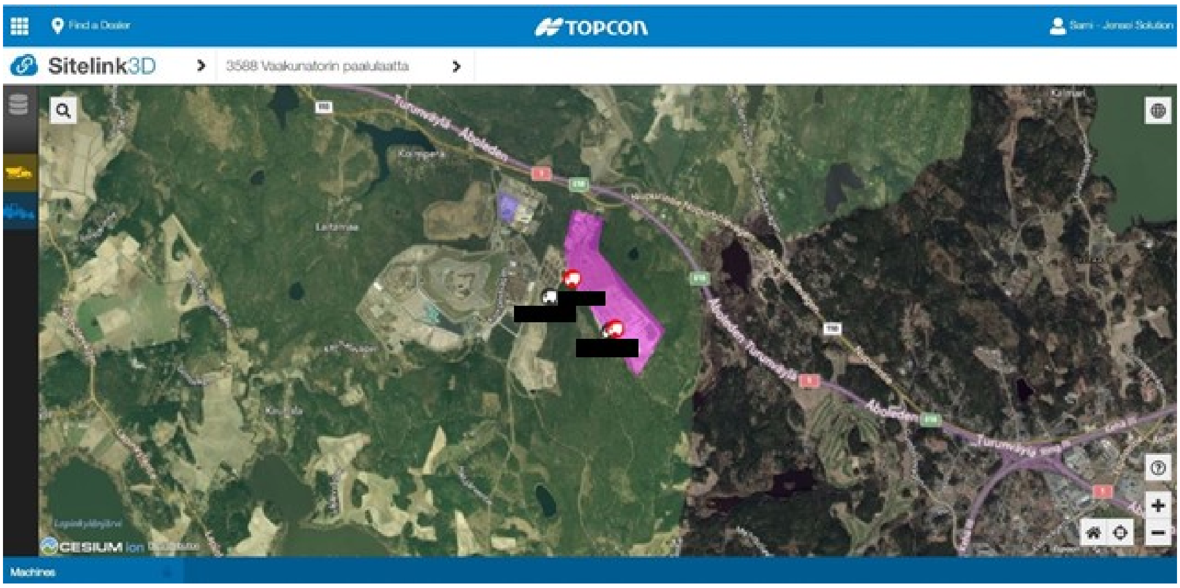
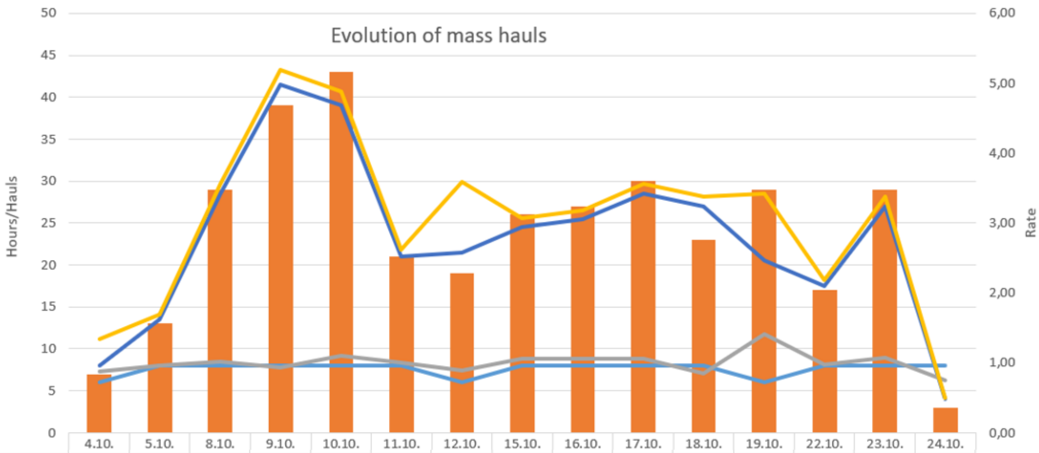


Figure 18. Four trucks simultaneously at unloading location. Identifying information censored.

It was also noticed that land pit’s lunch breaks resulted longer cycle times than they should have. Thus, land pit open hours have notable effect on excavation and mass hauling process. Had it been open for whole day, more hauls could have been executed in a day, as the flow of material would have been more stable. Truck operators might have wanted to have breaks at the same time which could also have resulted queuing.

6.2.4 Poor utilization of the excavator

Using the data gathered by the real-time tracking system and by in-site observations it was noticed that excavator was utilized poorly. Evolution of mass hauls is showed in Figure 19. The performance of the process can be evaluated by looking at both the rate of mass hauls per truck hour, and the rate between truck hours and excavator hours. Larger rate value between mass hauls and truck hours means that more hauls are delivered per paid truck hour, thus higher value represent higher utilization of the trucks. Larger rate value between truck hours and excavator hours means that larger number of trucks are handled with less excavator hours, thus higher value equals higher utilization of the excavator. Together, these two rates represent the overall performance of the process.



	4.10.	5.10.	8.10.	9.10.	10.10.	11.10.	12.10.	15.10.	16.10.	17.10.	18.10.	19.10.	22.10.	23.10.	24.10.
Mass hauls	7	13	29	39	43	21	19	26	27	30	23	29	17	29	3
Truck hours	8	13,5	28,5	41,5	39	21	21,5	24,5	25,5	28,5	27	20,5	17,5	27	4
Excavator hours	8,00	6,00	8,00	8,00	8,00	8,00	6,00	8,00	8,00	8,00	8,00	6,00	8,00	8,00	8,00
Rate Mass hauls / Truck hour	0,88	0,96	1,02	0,94	1,10	1,00	0,88	1,06	1,06	1,05	0,85	1,41	0,97	1,07	0,75
Rate Truck hours / Excavator hours	1,33	1,69	3,56	5,19	4,88	2,63	3,58	3,06	3,19	3,56	3,38	3,42	2,19	3,38	0,50

Figure 19. Evolution of mass hauls during the field experiment

Analyzing the utilization rates of truck and excavator it can be established that the global performance was highest on 10.10.2018. Therefore, all other days when rates have been smaller, either trucks or excavator were not used for their full potential. 224 hauls were performed after 10.10.2018. In total 355 hauls were performed. If actual performance from 10.10.2018 with five trucks would have been continued during the rest of the field experiment it can be estimated that the rest of the hauls could have been done in 204 truck hours and in 42 excavator hours. Thus, excavation and mass hauling phase would have ended approximately 4 days earlier. This is reduction of 26,32% to excavation phase duration. Even earlier if this performance level would have been reached sooner than 10.10.2018.

Maximum actual performance can be assured by analyzing the average time between loads and average cycle times for the same day. Time between consecutive loads is the time excavator had taken to load the truck. Values influenced by the breaks were manually identified from the data and removed in order to obtain real time between hauls and more accurate cycle times. On 10.10.2018, average loading time (with n=33) was 8 minutes 57 seconds. Evolution of the loading time is presented in Figure 20.

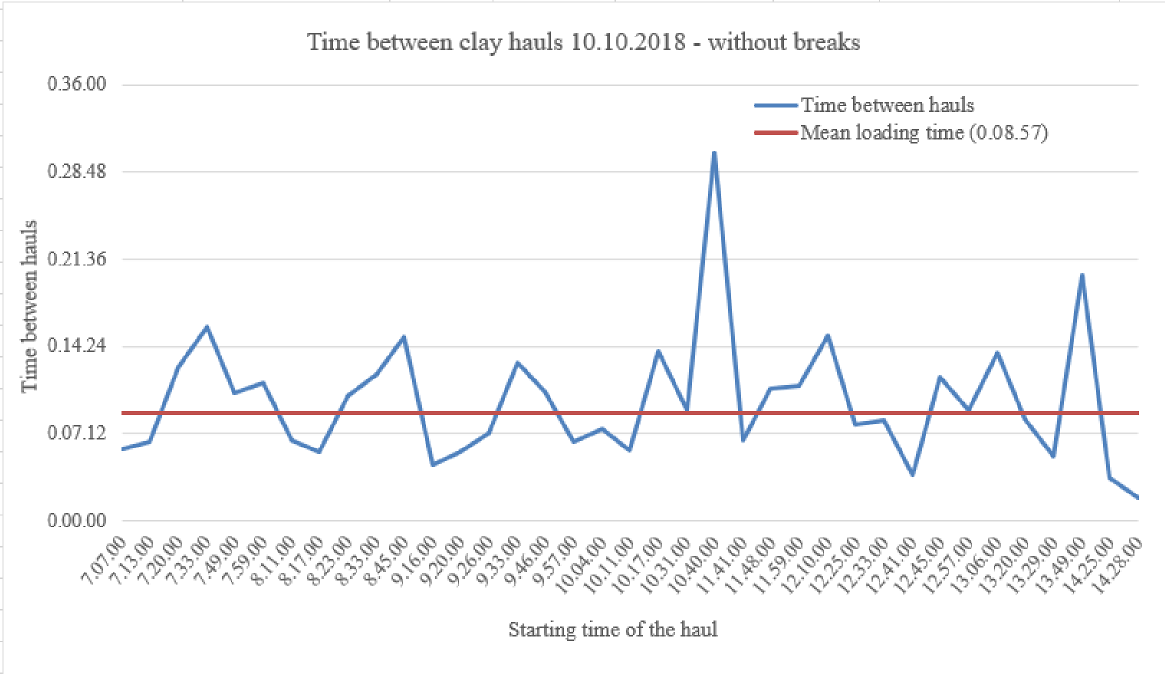


Figure 20. Time between hauls on 10.10.2018.

When average cycle time for the same hauls is 46 minutes and 26 seconds, it can be calculated that after loading the first one, excavator operator is able to load five trucks before first truck is going to return from hauling trip. Thus, maximum number of trucks for one excavator is six in this case considering that the situation and conditions stay the same. However, this calculation does not consider breaks or variance of other factors (e.g. traffic, material parameters), which will result queuing of the trucks. Thus, six trucks is not feasible for this situation and five trucks is the practical maximum number of trucks. Using this average loading time value from one day, total number of hauls and actual time spent during the whole phase, it can be estimated that the excavator operator used approximately 46% of his time loading the trucks. All other time was either cutting the soil in advance, idle or waiting for the trucks.

As previously shown, the highest possible number of trucks for this situation is five. More trucks would have resulted one truck having to wait all the time. In case that buffer is wanted to prevent trucks having to wait due to larger variances in cycle-time, four trucks could be assigned. Figure 21. shows cycle time distribution histogram on clay hauls during the test period. Clay haul cycle times influenced with breaks are manually removed to only examine the values of actual clay cycle times. Also, hauls not completing the full cycle were removed (e.g. last haul of the day or hauling crushed rock on the way back).

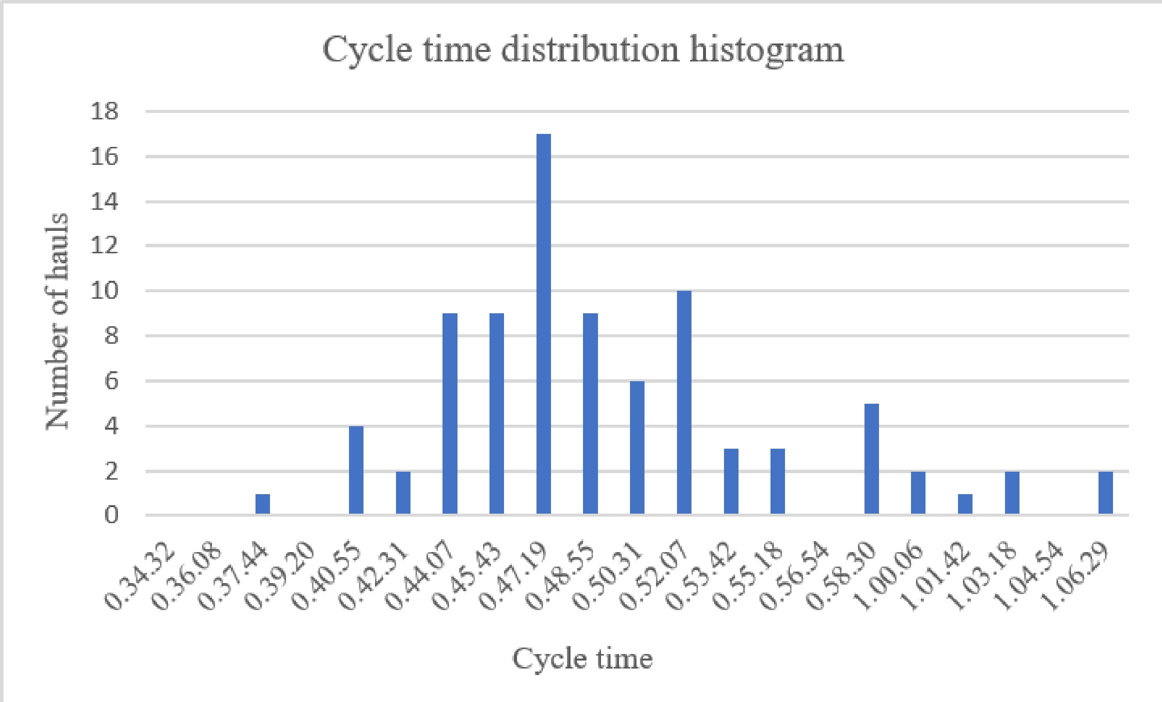


Figure 21. Cycle time distribution histogram.

Figure 21 shows the number of hauls closest to each cycle time value. As Figure 21 distribution shows, clay cycle times resembles normal distribution excluding the higher values. Distribution is gathered from 92 clay hauls. Only clay hauls that are not affected to breaks is included, in order to evaluate the normal cycle time duration. Also, other than clay materials are not included as they have separate unloading location and cycle time. Average cycle time of this data set is 50 minutes and 31 seconds and standard deviation is 7 minutes and 59 seconds. Highest frequency of haul cycle times is slightly below mean value. 79% of all cycle times are inside the standard deviation of the mean value. 92% of all cycle time values are inside two standard deviations of the mean value. Coefficient of variation for the clay hauls is 15,80%. Results indicate that cycle times are quite constant values and high buffer is not necessary as majority of material is clay. Although, large singular variances when having different material or traffic delays might result queuing of the trucks and larger cumulative waiting time.

Considering that higher buffer would have been used for the loading of the trucks and field test had been executed with constant four trucks, it can be estimated that this had resulted approximately 21% decrease in excavation duration and similar reduction to excavator related costs. Consider having the test executed with three trucks for the whole duration, excavation had ended approximately same time as it did with varying number of trucks.

6.2.5 Too long break times

The real-time tracking system in use did not separate truck operators time used for breaks. Thus, during the coffee breaks and lunch break haul cycle times increased for the duration of the break. However, cycle time increased more than the suitable duration of the break. This was fifth identified area for improvement. Figure 22 shows breaks' effect on the clay cycle times. Normal cycle time is calculated manually identifying clay hauls that was executed between break times. Cycle times during breaks were manually identified from clay hauls data and values were reduced with the corresponding time of the break. Coffee break cycle times were reduced with 15 minutes and lunch break cycle times with 30 minutes. Only clay hauls were used to have enough hauls for comparison. Other materials would not have had enough hauls during each break. Also comparing cycle times with different materials is not reasonable as they are hauled to different location and have different cycle times. As a basis for normal clay cycle time 92 hauls were used, coffee break 9.00-9.15 had 25 hauls, lunch break 11.00-11.30 had 22 hauls and coffee break 13.30-13.45 had 26 hauls. Known divergencies and errors were removed from the data.

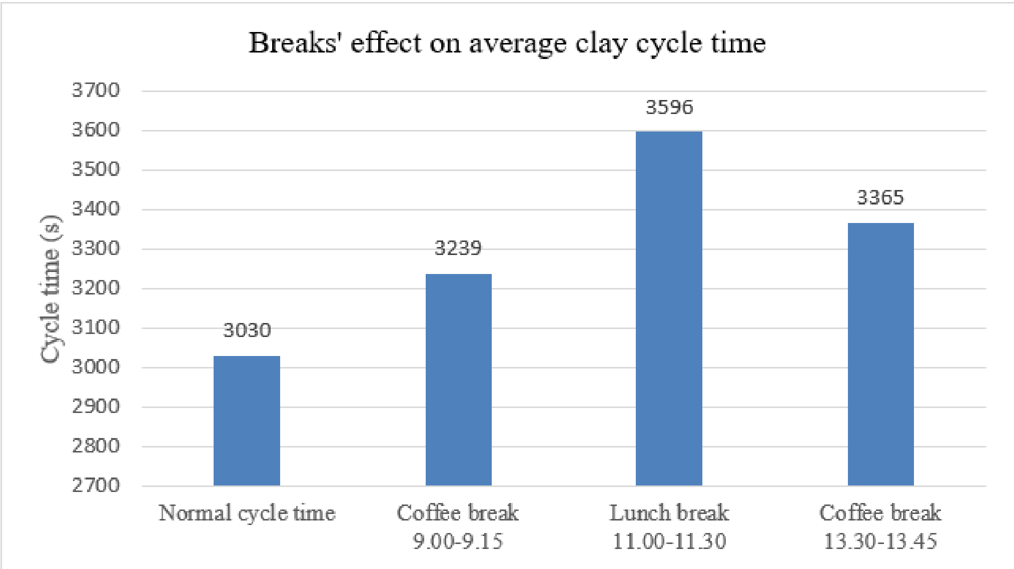


Figure 22. Breaks' effect on average clay cycle time.

As Figure 22 shows, average clay cycle time was 3030 second before and after breaks. First coffee break increased average cycle time by 6,90%. Lunch break increased average cycle time duration by 18,68%. Last coffee break resulted increment of 11,06% to average cycle time. Results indicate that time used for breaks were too long.

Increment during the lunch time could be explained with land pit restrictions. In case trucks arrived land pit in unpleasant time they first had to wait for land pit to open before having their own lunch break. In addition, lunch breaks might have required truck operators to drive to restaurant before starting their break. There is not any clear reason why second coffee break resulted larger increment to cycle times. Contrary, it would be more reasonable to have longer cycle time durations in morning hours due cycle times being more influenced to traffic rush hours. During the second coffee break traffic conditions were observed to be more fluent. Results indicate that durations of the breaks increase during the working day. This might be due to socializing or fatigue of the workers and operators. More research is needed to evaluate the proper reason.

6.2.6 Insufficient loading of the trucks

Insufficient loading of the trucks was identified to be one potential area for improvement. This was identified by comparing actual hauled volume and theoretical excavated volume. Prior to excavation phase original surface level of the construction site was surveyed by surveying engineer. During the excavation the cut surface was surveyed to get bulk volume difference of the original surface layer and cut layer. After the excavation phase, top of crushed rock layer was surveyed to get bulk volume difference of the crushed rock that was not hauled away from the site. Figure 23 shows the surface model of the surveyed crushed rock layer.

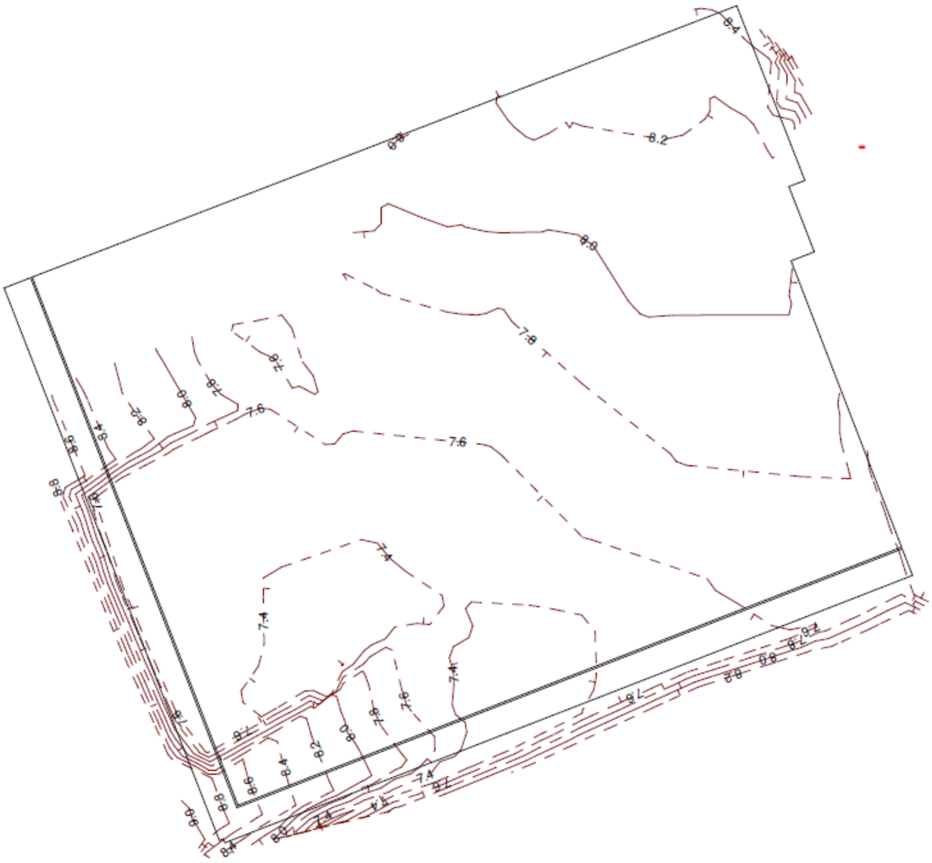


Figure 23. Surface layer of the crushed rock.

The surface level of crushed rock was surveyed at the end of the excavation phase. Due to this, two access ramps are visible in the surface layer. This situation was used for a calculation basis. Topcon's Sitelink3D web interface gave total volume of hauled mass for the same time period and data was manually corrected with known misuses of the application. Total hauled volume equaled to 4659,5 cut-cubic-meter (m3itd). Difference between original surface level and excavated surface level is 2877 bulk-cubic-meter (m3rtr). Difference between compacted crushed rock fill layer and excavated surface is 862 bcm (m3rtr). Volume of bought crushed rock is 400,4 bcm (m3rtr). Volume of original crushed rock fill is 461,6 bcm (m3rtr). Thus, volume of total cut material is 2476,6 bcm (m3rtr). Converting multiplier for transferring bulk-cubic-meter bcm (m3rtr) into ccm (m3itd) is different for each material. According to InfraRYL (2015) material state multiplier for clay is 1,68. Calculation is simplified to use only clay multiplier. This is because clay hauls could have included small volumes of crushed rock in every haul, thus not knowing real volume of clay and crushed rock volumes. Total excavated volume is 4160,7 ccm (m3itd). Difference between total excavated volume and hauled volume equals to 498,8 ccm (m3itd). Ideally there would not be any difference if proper loading of the trucks would occur. Thus, fill percentage of the trucks have been on average 89,2% during the test phase. Insufficient loading of the trucks has resulted approximately 34 extra haul cycles.

Previous calculation is not accurate and can include manual errors during the surveying part or converting the masses to different unit. Although the result corresponds to observations done in construction site. Site Manager identified trucks not being always fully loaded and noticed the excavator operator to improve the filling of the trucks. Simply by filling the trucks to the fullest it is possible to improve hauling productivity significantly. Thus, insufficient loading of the trucks should be monitored more constantly. In this case it was not clear if insufficient loading of the truck was due to excavator operators experience or rush to load trucks all queuing trucks or both.

6.3 Control Actions

6.3.1 Control actions identified during the field experiment

Control actions were done to identified areas for improvement in the excavation and mass hauling process during the field experiment execution phase. These areas were too early ending of the truck operators work shifts and insufficient loading of the trucks. Control actions were verbal notifications by Site Manager to excavator operator. Control actions resulted better behavior in following days. Although, control actions did not result unsuitable behavior from not happening again. Thus, monitoring of these areas should be done frequently and automatedly. Automatized notifications on too early endings to Site Manager could potentially allow control action being done (e.g. calling to truck operator) in real-time and having them ordered to return to construction site for more hauls.

6.3.2 Future control actions

Real-time tracking of mass hauls produced large number of information which made identifying these potential areas for improvement challenging. Due to this all areas could not be identified while real-time tracking system was in use. To be able to monitor right areas in the produced data it is important first know what to look at. In this field experiment these areas were identified to be too early ending of the truck operators work shift, route decisions, queuing of the trucks, too long breaks, poor utilization of the excavator and insufficient loading of the trucks. In order to take potential areas for improvement into account next time similar field experiment is conducted, recommended control actions are formulated to improve use of control actions and improve performance during the execution phase.

Too early ending of the truck operators work shift could be analyzed automatically, and notifications sent to truck operator if enough time is not left to return to be loaded and haul material unloading area before either ending of working time or closing of land pit. Enough time consists of actual cycle time between excavating and compacting fronts. In cases where truck operator ends day too early, notifications should be sent to Site Manager.

Currently, many construction sites have not identified bad route decisions of truck operators as a problem. It might be that is route decisions have been too hard to monitor and variations in cycle times are considered normal. The route decisions for the trucks could be decided after first trying different routes and choosing the shortest in cycle duration. In case where cycle times are close to same, shorter route in distance should be selected to decrease maintenance costs. Notification should be sent to Site Manager if truck operator uses different route than what is assigned. If the optimal route varies, truck operators could be asked to use navigation services that utilizes automatize vehicle location (AVL) technologies along with data from other road users to select the optimal routes in different times of the day (e.g. Google Maps). These routing technologies could potentially forecast potential problems and help to avoid traffic jams and suggest alternative routes instead. There is great potential for improvement in managing routes in earthwork logistics.

Queuing of the trucks could be monitored better utilizing intelligence location-based information systems. If a truck has unloaded the material and returned to loading area and another truck is still being loaded, waiting time counter could be started as soon as the truck stops. Used real-time tracking system does not calculate queuing time of the trucks and wasted time is not easily identified from the data. Queuing times are included in the cycle times which result larger cycle times. In order to better monitor queuing times properly automatize queuing time data is required. Queuing can be reduced by changing starting times of each truck to suitable steps. Steps should be close to the average loading time. In addition, breaks could be included into the real-time tracking system to better identify time used for them.

Poor utilization of excavator could be avoided with better managing and monitoring the loading capacity of the excavator and cycle times of the trucks to identify optimal number of transporting equipment. Naturally, in all cases it is not possible to have optimal number of trucks due to limitations set by other tasks, external conditions or availability of equipment. Although, in many cases it would be possible to improve the utilization rate of the excavation equipment. Knowing when it is possible to add resources requires identifying possible risks in advance which requires experienced management. Adding too many trucks for each excavator results unproductive performance. Thus, monitoring is essential tool for manager to estimate when excavators are used for their full potential. Automatized notification could be sent to the Site Manager when either excavators or trucks exceed certain waiting time or utilization rate limit.

Too long break times could be monitored with the system automatically. Too long breaks will increase time used for waiting. It is not clear how the excavator operator acted during this test period as this was not measured. Considering that only truck operators had too long breaks, waiting time of the excavator increased. Considering that if also excavator operator was having longer break times, cumulative waiting time of trucks increased. Monitoring the time used for the breaks automatically would allow the Site Manager to better supervise the issue. Notifications could be sent to persons exceeding the allowed break time during the day and exceeded time could be automatically reduced from billable hours. It seems quite probable that largest increment to cycle times was due to lunch break of the land pit. Having an alternative land pits could decrease cycle times during the lunch hours. In addition, performance could be improved with better instructions when to have lunch break. For example, considering that truck operator would arrive to land pit after its closing for the lunch break, truck operator could be assigned to have its lunch break before proceeding to land pit. Anticipatory actions could decrease time used for waiting. Previously mentioned routing technologies could potentially forecast arriving time to land pit. Thus, problem could be identified beforehand and removed by having lunch break for optimal time.

Insufficient loading of the trucks could be monitored with regular (e.g. weekly) volume comparisons between actual excavated mass and hauled mass. Currently, construction sites have not identified this as a problem. This might be due that filling percentage of the trucks is not easy to identify visually form ground level. Filling percentage and loading time of the trucks are both skills that separates a bad excavator operator from a good one. However, it is peculiar that volume filling percentage is not constantly monitored. This allows excavator operator being able to wrongfully increase apparent performance by doing incomplete loadings. Monitoring the filling percentage of the trucks would set performance limit to the excavator operator. Obviously, too large fillings of the trucks should not be performed. Legal regulations have certain limits that should not be exceeded to avoid being dangerous to other road users or risk having to pay a large fine. Overfills depend on the density of the hauled material. Monitoring hauled material suitable filling percentage of the trucks could be estimated better for each material. Actual excavated mass can be calculated with existing technologies (e.g. surveys, photogrammetry). With real-time tracking of mass hauls these values could be compared to estimate the filling percentage.

In addition to improving monitoring and management practices to increase performance in identified areas, better procurement should be performed. Traditional hour-based contracts for excavator and truck operators does not encourage to efficiency. Contracts could be done on performance basis. Real-time tracking systems allow automatized monitoring of the performance. However, the unit as basis of billing should be appropriate. Using number of hauls or hauled volume might not lead to optimal result as it does not necessarily mean full truck loads. Unit should be actual weight of the hauled mass or actual excavated volume. However, using these units is not convenient as they might be difficult to obtain.

6.4 Accuracy of the Haul Truck Application

During the field experiment truck operators used simultaneously the Haul Truck application and filled paper transport documents. These traditional paper transport documents were used as basis for billing. Paper transport documents were given to general contractor from 2 to 4 weeks after work had been done. After so long time, it would have been difficult to verify the documents without the Haul Truck application.

To study the suitability of the Haul Truck application data to be used as basis for billing, haul data were compared to paper transport documents. In this context accuracy means that information collected with two different sources matches. Results are shown in Figure 24.

Truck	Haul application	Paper documents	Accuracy
1	53	70	76 %
2	94	95	99 %
3	23	25	92 %
4	23	23	100 %
5	95	96	99 %
6	43	46	93 %

Figure 24. Accuracy of the information provided by the Haul Truck application.

As Figure 24 shows one operator managed to have matching information on both haul truck application and on transport documents. Two operators managed to 99% accuracy, two managed over 92% accuracy and one managed to achieve 76% accuracy. Compared hauls included both materials hauled from the site, and materials hauled into the site. Some of the errors in hauls were due to missing instructions on some materials and some was due to misuse of the application. Construction site included small number of materials that were not known prior excavation. These materials were light aggregate materials and bricks. To prevent loss of information Haul Truck applications material selection should be designed to include also materials that are not known prior construction. This can be done at SiteLink3D when setting up the construction site. In addition, clear instructions should be given for all material that is hauled in and out of the site. Operators had different experience using tablets which may have been contributing factor in results.

Even though data provided by the Haul Truck application did not present right number of hauls, it allowed verification of each hauls. The used route and times were able to be verified. Large cycle times and their route visualization allowed to identify if hauls had been performed without using the Haul Truck application in the right way. Thus, right number of hauls could be verified manually. In terms of reliability and transparency, swift data provided by the Mass Haul application is more desirable than using paper documents which are obtained weeks later. Achieved accuracy also suggest that it is possible to have same information on Haul Truck application that was in paper documents. Thus, paper transport documents could be removed. However, when using real-time tracking, instructions should be clear to minimize the number of manual corrections. In case the operator is not experienced with mobile devices more thorough introduction should be held.

6.5 Other Uses of Data

Haul Truck application provides large number of performance data. The data is stored in the cloud for future use, whereas traditional paper documents might get lost and require more manual work to obtain the wanted information. Thus, real-time tracking systems allow creation of historical database of past projects with fast and easy access. This data can be used in future project as a basis for designing the operations with similar characteristics. However, data cannot be used for all projects as every project includes own unique characteristics. Gathering data from different projects allows more precise estimating of actual performance for different cases. Garcia et al. (2006) proposed the use of real-time tracking system to collect traffic data near construction site to get information for designing the construction operations. Utilizing real-time data for simulation purposes can also increase the accuracy of the simulation. Song and Eldin (2012) estimated that data provided by real-time tracking data helped to estimate truck cycles delay of 16,3 min and reduce trucks cycle-time prediction error by 6%. These researches suggest that real-time tracking systems could provide benefits to planning and designing phase.

In addition, more precise performance data allows better comparison of different subcontractors. As excavator operator has large impact on performance of the excavator as well as for the whole excavation phase, real-time tracking data allows estimating the value of each operator. Considering if subcontractor with larger machine is slower in excavating and loading than another subcontractor with smaller machine, more cost-efficient option can be selected. Obviously, conditions (e.g. material) need to be similar when comparing different operators. Value of the operator is currently not well defined, even though operator skills varies significantly. Performance based selection could motivate excavation operators to work more efficiently and to improve their skills. Therefore, real-time tracking system could provide benefits to procurement phase.

Real-time tracking system can also improve Quality assurance processes as material origin and destination can be verified afterwards. With traditional paper documents this is not possible as markings can be unintentionally or on purposely incorrect. Especially with contaminated soil material and material classified as waste (e.g. old concreate foundations or pipelines) it is possible to ensure that material is delivered to proper locations. Similarly, the amount of aggregates from different crushing plants can be verified to ensure that all material is from certified suppliers. Previously this had not been possible.

Real-tracking system can also improve sustainability as the material delivery routes and times can be verified. This allows more precise calculation of emissions and greenhouse gases. Previously these calculations have been difficult as the routes of the trucks have not been known and traffic delays or other factors might not have been considered.

6.6 Simulation

According to Berner et al. (2013), especially logistics can be examined with simulations to enhance reliability and productivity of the process. As Agile Earthwork Optimization method was designed after the field experiment phase, it could not be tested in the actual situation. To prove the utility of the Agile Earthwork Optimization method is simulated in this Section using data gathered from real-time tracking of mass hauls in field experiment. According to Hevner et al. (2004) experimental simulation for design science is suitable evaluation method. Actual real-world data gives external validity for evaluation.

Designing the optimal allocation starts from the last task of the production line. In field experiment last task of the production line was unloading at the land pit. Between Monday and Thursday land pit was open from 7.30 to 11.30 and from 12.00 to 16.00. On Friday land pit was open from 7.30 to 11.30 and from 12.00 to 14.15. Thus, working hours for excavator should be from Monday to Thursday from 7.00 to 15.30 and on Friday from 7.00 to 13.30. Trucks could be assigned to arrive between 7.00-7.30 and end between 15.30-16.00 on Mondays to Thursday and between 13.30-14.00 on Friday.

Land pit open hours sets limits to unloading capacity. Maximum unloading capacity depends on loading capacity and number of excavators. Size of the construction site is so small that having more than one excavator might not be effective. Also, limited access possibilities might restrict trucks moving in and out of the site. Thus, only one excavator is assigned. Loading capacity along with cycle time duration sets optimal number of trucks.

Although, surface materials (e.g. asphalt, stones, curbs) are not hauled to same land pit as clays, so first allocation needs to be designed according to these materials. Also, peeling of the surface materials might take more time as excavator needs to move more. Thus, Site Manager could allocate only one truck to begin the project with. As spreading and compacting is excluded from the process, only cycle times of the trucks and loading time of excavator is monitored.

Figure 25 shows the simulation with actual average loading times and cycle times that field experiment resulted. Average values are collected from all hauled material during each day. Although, known divergencies and errors were manually removed. Average cycle time values are used to determine number of hauls that is possible to be hauled in a day. First day loading time is estimated because data was not available as only one truck was used and loading time between different trucks could not be obtained.

		Number of			Average			Utilization rate of		
Day	Working hours	Excavators	Trucks	Hauls	Loading time	Cycle time	Major material	Excavator	Trucks	Suggested action
1	8	1	1	6	0:15:00	1:10:00	Surface layers	18,75 %	87,50 %	Add two trucks
2	6	1	3	15	0:09:06	1:01:10	Surface layers	37,92 %	84,95 %	Add one truck
3	8	1	4	32	0:08:23	0:49:08	Clay layers	55,55 %	81,89 %	Add one truck
4	8	1	5	40	0:09:18	0:51:07	Clay layers	77,50 %	85,17 %	
5	8	1	5	40	0:09:16	0:48:13	Clay layers	77,22 %	80,33 %	
6	8	1	5	40	0:11:06	0:50:45	Clay layers	92,50 %	84,50 %	
7	6	1	5	30	0:08:53	0:49:01	Clay layers	74,17 %	81,66 %	
8	8	1	5	40	0:10:18	0:50:10	Clay layers	85,83 %	83,61 %	
9	8	1	5	40	0:09:55	0:53:17	Clay layers	82,50 %	88,83 %	
10	8	1	5	40	0:09:30	0:55:16	Clay layers	79,17 %	88,83 %	Remove one truck
11	8	1	4	32	0:11:30	0:57:04	Clay layers	63,33 %	88,83 %	Remove all equipment

Figure 25. AEO simulation using data obtained from field experiment.

As Figure 25 shows, after the first day utilization rate of excavator and trucks is calculated. Utilization rates are calculated multiplying number of activities with the time it takes to conduct the activity, and this is divided with available working hours. For example, on first day six hauls were performed with average cycle time for that day being 1 hour 10 minutes. Thus, utilization rate of truck is 1 hour 10 minutes multiplied with six hauls and divided with 8 hours of working. Utilization rate of excavator is similarly calculated, multiplying loading time with number of hauls (loading activities) and dividing with available working time.

Analyzing the utilization rate of the equipment allows estimating the optimal number of earthwork equipment. For this simulation target utilization rate is set to 70% for the excavator and 80% for the trucks. Too many trucks would result dropping of utilization rate of trucks as more time is wasted on waiting and less hauls are performed in a day. As Figure 19 shows, first day utilization rate of excavator is 18,75%. Adding two more trucks should increase utilization rate of excavator over 50%. However, on second day utilization rate is just 37,92% due to improved average loading time. Utilization rate of trucks did not drop below 80%. Thus, one more truck can be assigned. On third day, utilization rate was just 55,55% due to change of major hauled material, which resulted faster average loading time and cycle time. Utilization rate of trucks did not drop below 80%. Thus, one more truck can be assigned. On fourth day, utilization rate of excavator was above target value, thus no actions needed to change equipment allocation. Utilization rate stayed above 70% for the rest days excluding the last day. Total number of hauls was 355. After the tenth day, only 32 hauls were assumed to be left. Thus, one truck should be removed as last hauls can be transported with only 4 trucks.

Looking at variations in excavation utilization rate it can be conducted that having more trucks could have resulted the excavator utilization rate close to 100% on more days which could have resulted more time used for waiting. This would have shown decrease in utilization rate of trucks. Similarly, if materials had changed or other obstacles had occurred, average loading times and cycle times had changed. Thus, adaptation to different situations could have been done.

Comparing actual performance from field experiment and simulation with Agile Earthwork Optimization method with data obtained from the field experiment, it can be conducted that AEO simulation resulted 30 hours reduction in excavator operating hours. This is 26,3% reduction in duration of the excavation phase. Next phases could be started 4 days earlier. If excavator cost is 80€/hour potential savings are 2 400€. If scope of the excavation phase would be larger, more costs are reduced. Figure 26 shows comparison to a situation where excavation phase lasts for a year.

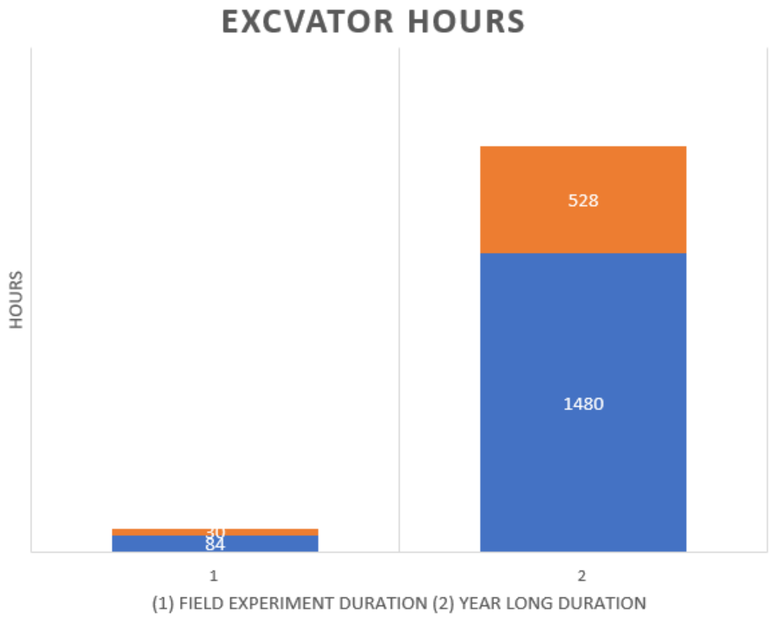


Figure 26. Excavator hours in yearlong project.

As Figure 26 shows, using AEO method in a yearlong excavation phase in a similar project potential savings could result reduction of 528 excavator hours which is 42 240€ savings for each excavator. In addition, more savings would occur from reduced overall duration of the project. Considering each month has approximately 160 hours of working time, excavation phase could be finished more than 3 months earlier. Similarly, total project duration could be reduced same amount.

AEO method has large potential for improved performance and reduced durations in earthworks. This simulation was done manually which is time consuming. These results do not include the time needed to monitor and analyze the real-time tracking system. Hours used for this activity was not measured. Therefore, total improvement on productivity is less than what is achieved with reduction of excavator costs and shorter duration of a construction phase. In order to get the full benefit from the AEO method steps should be done automatically. Simulation utilizes real data from the field experiment. However, it does not include actual effects of the actions to utilization rates. Although, using actual information from the field experiment it presents good estimate on what is possible to improve. More research is needed to test the AOE method's feasibility in different projects and in varying conditions.

6.7 Limitations

In this section the research limitations are described. This thesis includes investigation of one unique infrastructure project, although the earthwork process includes the same steps also in other projects. Using only one case project sets limitations to the focus of this thesis. In this study, the focus is on excavating and hauling process. Spreading and compacting activities will not be investigated closely. Reason for this is that case project did not include these activities in the normal earthwork process. Although, spreading and compacting activities are considered in the developed optimization model.

Another limitation for this study is the length of the excavation phase in the case project. Three weeks test phase will limit the possibility to identify areas for improvement during the test phase, conduct control actions and see their effects. Although, possible control actions for later identified areas are considered in this thesis. However, the results of some of the control actions cannot be determined in the case project.

7 Conclusions

7.1 Research problem and Objectives

Productivity growth of construction industry has been lagging for long time. Construction industry's poor productivity may result from different attributing factors such as project uniqueness, weak utilization of technology and poor management (Allmon et al. 2000). Changing environmental factors such as location, landscape and weather along with varying project personnel makes managing the project challenging (Kirchback et al. 2014).

However, transportation industry has managed to increase productivity albeit it is subjected to similar unique aspects as construction industry (e.g. varying location and weather conditions). This may be due to the fact that transportation industry utilizes more passive data collection methods. While in construction industry data collection is done manually (Navon et al. 2004) transportation industry has adopted ITS (intelligent transportation systems), AVL (automated vehicle location) and AFC (automated fare collection) technologies which have shifted the industry from a data-poor environment into a data-rich environment (Ma and Wang, 2014). In the past, transportation industry had a problem that traditional data collection methods were costly and inaccurate (Simon and Furth, 1985). Construction industry is still suffering from similar problems which may be a contributing factor why its productivity development has been lagging.

Researchers have observed that not enough effort is done at construction site to gather reliable data and the collected data is not distributed well (e.g. Laufer and Tucker, 1987). This may be because manual data collection is too time consuming or proper technologies have not yet been introduced. Insufficient data collection methods lead to problem being longer undetected (Navon and Tucker, 1987). The longer incorrect behavior remains undetected, the larger is the potential damage it can cause. There is a need for automated data collection to enable better management that can take corrective actions in real-time (Sacks et al. 2003).

Real-time tracking technologies have been shown promising results answering to the need for automating data-collection and real-time management. The main objective of this study is to investigate the excavation and mass hauling process of an infrastructure construction project with a real time-tracking system. The following specific objectives and research questions were formulated and addressed in the study:

Objective 1
To design optimization model for excavation and mass hauling process.

1. What is the optimization model for excavation and mass hauling process using real-time tracking system?
2. What are the benefits of using this optimization method?

Objective 2
To identify areas with potential for improvement in excavation and mass hauling process and make control actions to improve performance.

3. What potential for improvement were identified?
4. What control actions were done?
5. What were the results of control actions?

Objective 3
To estimate the other benefits using the real-time tracking system.

6. Could the collected data be used to remove using paper documents?
7. What is the other possible use of the data?

Excavation and mass hauling process can be considered as a subprocess of the production process. The production process can be building construction project or infrastructure construction project. The overall production cost is minimized when the cost of each subprocess is minimized (Koskela, 2000). The cost of subprocess is minimized when non-value adding activities are removed or minimized. All objectives aim to reduce waste from the production and thus reduce lead time and increase productivity.

7.2 Reaching objectives of the study

7.2.1 Objective 1

The first objective was to design an optimization model for excavation and mass hauling process. Current mass haul optimization techniques do not consider real-time tracking information. In order to achieve full potential of real-time tracking system solutions excavation and mass hauling process needs to be redesigned too. Two research questions were formulated to answer this objective.

1. What is the optimization model for excavation and mass hauling process using real-time tracking system?
2. What are the benefits of using this optimization method?

First research question was answered with designed artifact, Agile Earthwork Optimization method. The earthwork process is optimal when allocated equipment's are utilized properly. Using the AEO method it is possible to adopt the earthwork equipment allocation to different situations. Varying conditions demands quick reactions to be efficient. The designed AEO model is simulated using a case project data to demonstrate and evaluate utility of the solution. Simulation resulted 26% reduction in the excavator operating hours. Same percentage could be reduced from the excavation phase duration as well as the overall project duration. Reduction of the project duration would also decrease overall costs.

Potential benefits using the AEO method depends on the project characteristics and the volume of earthworks. The AEO was simulated using data from one project. In order to get more accurate estimates more simulations could be made with data obtained from different project conditions and different size of projects. Having similar conditions as in the case project, it can be estimated that potential savings can be significant. In a yearlong project proper use of machinery could reduce duration over 3 months in some projects.

These results do not include the time needed to monitor and analyze the real-time tracking system. Hours used for this activity were not measured. Therefore, total improvement on productivity is less than what is achieved with reduction of the excavator costs and shorter duration of the construction phase. To get the full potential out of real-time tracking system, it should be able to analyze the data and send notifications automatically. Also, real-time tracking data should be reliable in order to use it without need for manual corrections. This requires clear instructions for a truck operator and operators having to go through learning process for new methods.

7.2.2 Objective 2

The second objective of this study was to identify areas with potential for improvement in the excavation and mass hauling process and make control actions to improve the performance. Three research questions were formulated to answer this objective.

3. What potential areas for improvement were identified?
4. What control actions were done?
5. What were the results of control actions?

Prior being able to do any improvements, problem identification is required. In the studied project areas with potential for improvement were too early ending of the truck operators work shift, route decisions, queuing of the trucks, poor utilization of the excavator, too long break times and insufficient loading of the trucks. Out of these areas, too early endings of the trucks and insufficient loading of the trucks resulted in control actions due being identified during the test phase. Rest of the improvement areas were identified after the test period while analyzing the gathered data. Control actions were designed also for these areas.

Too early endings of the trucks resulted notification from the Site Manager to the excavator operator to use whole available time for loading hauls. Actual cycle time data gathered with the real-time tracking system allowed to set certain time for appropriate ending. Control actions resulted improved behavior, although it did not prevent bad behavior occurring again. In addition, insufficient loading of the trucks resulted similar notification from Site Manager to the excavator operator. However, it is not clear if this had any effect as insufficient loadings were not monitored regularly.

Control actions designed for later use for identified areas included using of automatized notification on too early endings, using of preselected routes or navigation services (e.g. Google Maps) in order to use optimal routes, improving queuing time monitoring, automatized utilization rate of equipment, regular volume comparisons to identify filling percentage of the trucks and using of routing technologies to forecast arriving times to land pit or construction site and have better instructions what to do in different situations. Potential benefit of these control actions should be tested in future studies.

Designed control actions have a great potential to increase the productivity of the construction sites. Using the real-time tracking system clearly enhanced identifying potential areas for improvement in the earthwork process and allowed the Site Manager to do control actions based on actual results. Bad route decisions might have not been identified without the real-time tracking system. This is hard to monitor using traditional observative methods with limited time for monitoring. For that reason, these findings were significant. In addition, real-time tracking system allowed calculation of utilization rate of earthwork equipment which will help site management designing the optimal equipment allocation.

7.2.3 Objective 3

Last objective was to estimate the possible other benefits using the real-time tracking system. Two research questions were formulated to answer this objective.

6. Could the collected data be used to remove using paper documents?
7. What is the other possible use of the data?

The third objective examines further what other benefits use of the real time tracking system could provide. Traditionally the excavation and mass hauling process have generated a large number of paper documents and the data is left little to no use. In addition, it has been problematic to verify the data in the paper document afterwards. In this study data obtained with the Haul Truck application and the paper documents were compared. Similarity of the data was mostly over 99% in half of the truck operators. Two operators managed to achieve similarity of over 92% and one operator managed to achieve just 76% similarity. Compared hauls included both materials hauled from the site, and materials hauled into the site. Some of the errors in hauls were obtained to result from missing instructions on some materials. Construction site included small number of materials that were not known prior excavation. To prevent loss of information Haul Truck applications material selection should be designed to include also materials that are not known prior construction. This can be done at web interface when setting up the site. In addition, clear instructions should be given for all material that is hauled in and out of the site. Operators had different experience using tablets which may have been contributing factor in results.

Even though data provided by the Haul Truck application did not present right number of hauls, it allowed verification of each haul afterwards. The used route and hauling times were able to be verified. Large cycle times and their route visualization allowed to identify if hauls had been performed without using the Haul Truck application in the right way. Thus, right number of hauls could be estimated manually. In terms of reliability and transparency, swift data provided by the Mass Haul application is more desirable than using paper documents which are obtained weeks later. Thus, paper transport documents could be removed. However, when using the real-time tracking, instructions should be clear to minimize the number of manual corrections.

In addition to removing the paper documents real-time tracking could potentially enable other improvements. The system could allow creation of historical database of past projects and their costs. Actual performance measures along with cost data could potentially help estimating the costs of future projects. This improves data storage and information flow as paper documents might get lost and requires more manual work to gather and process. In addition to improved information storage and distribution, large number of data provided by real-time tracking system could improve planning and designing phase by reducing simulation errors.

Real-time tracking system can also improve Quality assurance processes as material origin and destination can be verified afterwards. Real-tracking system can also improve sustainability as the material delivery routes and times can be verified. This allows more precise calculation of emissions and greenhouse gases. Previously these calculations have been difficult as the routes of the trucks have not been known and traffic delays or other factors might not have been considered.

Along with these benefits, real-time tracking data allows general contractor to evaluate excavator operators better. The excavator operator has large impact on performance of the excavator as well as for the whole excavation phase. Value of each operator can be determined based on their previous performance. Value of the operator is currently not well defined, even though operator skills varies significantly. Performance based selection could motivate excavation operators to work more efficiently and to improve their skills.

7.3 Reliability and validity of the research

Relevant scientific articles and researches were used in literature review. Scientific articles and researches were searched using Scopus database. Researches included articles on earthwork optimization, real-time tracking technologies and supply chain. Objectives of the study were achieved. Results were similar that what have been found on other studies.

Zhai et al. (2009) estimated that higher use of technological solutions resulted improvement of 31 to 45% in productivity in real life cases. Similar significant improvements could be achieved with the use of real-time tracking of mass hauls. Excavator costs of the case project could be reduced with 26% using the Agile Earthwork Optimizing method with real-time tracking system. More potential benefits could be achieved with reduced construction durations and improving all the identified areas in the process. In addition, similar scale results have been achieved by Parente et al. (2015), which estimated that optimal equipment allocation could potentially reduce costs and durations of construction phase from 20% to 50%.

Fadiya (2015) stated that current practices are still intuitive, which this study also confirms. Management decisions are based on their previous experiments in many situations. However, some of these experiences might not be optimal in terms of productivity. A practical example is the route decision of the truck operators in the field experiment. Operators used their previous experience selecting the routes even though some of the routes were not the shortest nor fastest. Thus, monitoring is needed to improve decision making and managing the project.

Results also support Heyl’s (2015) statement that construction projects lack the identification and consequently the elimination of possible bottlenecks. Real-time tracking systems offer a solution to identify and elimination of possible problems. Improved verification of billing hours was also observed in this study. Similar founding has been achieved by Costin et al. (2015) which stated that real-time tracking system improved billing and record keeping.

Data provided by the real-time tracking system might have been subject to human errors by truck operators which were not identified when analyzing the data. Even though, truck operators were introduced to the system at the beginning misuse of the application could have been occurred. However, it is probable that both positive and negative errors have been occurred which means that having larger number of data set average value (e.g. hauling time or cycle time) is quite accurate. However, it is also possible that manual identification of misuses of the application and removing this data might have affected the results a bit too optimistically as manual identification is also subject to human error. Although, in the field experiment most of the days were not subjected to other manual corrections than removing the break time values from the haul cycles. Thus, large majority of the data is unmodified.

7.4 Proposals for further research

This study focuses on understanding "what" factors are affecting to productivity of the excavation and mass hauling process and "how to" improve these potential areas for improvement. Findings presented in this study provides starting point for developing these actions further.

Real-time tracking systems produce large number of information. In order to get full potential out of real-time tracking system, system should be able to analyze the data automatically. In the future research focus could be how data could be analyzed automatically.

Future research areas could also focus to improve identified unproductive areas in the excavation and mass hauling process. These were too early ending of the truck operators work shift, route decisions, queuing of the trucks, poor utilization of the excavator, too long break times and insufficient loading of the trucks. Real-time tracking of mass hauls could also be used in different kind of project so benefits of the systems could be verified in other projects with different characteristics.

There might be also other possible areas for improvement in the excavation and mass hauling process that were not identified in this field experiment. Such areas could be varying traffic conditions and human factors. One interesting aspect would be to study if the queuing of the trucks effect on their filling percentage.

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